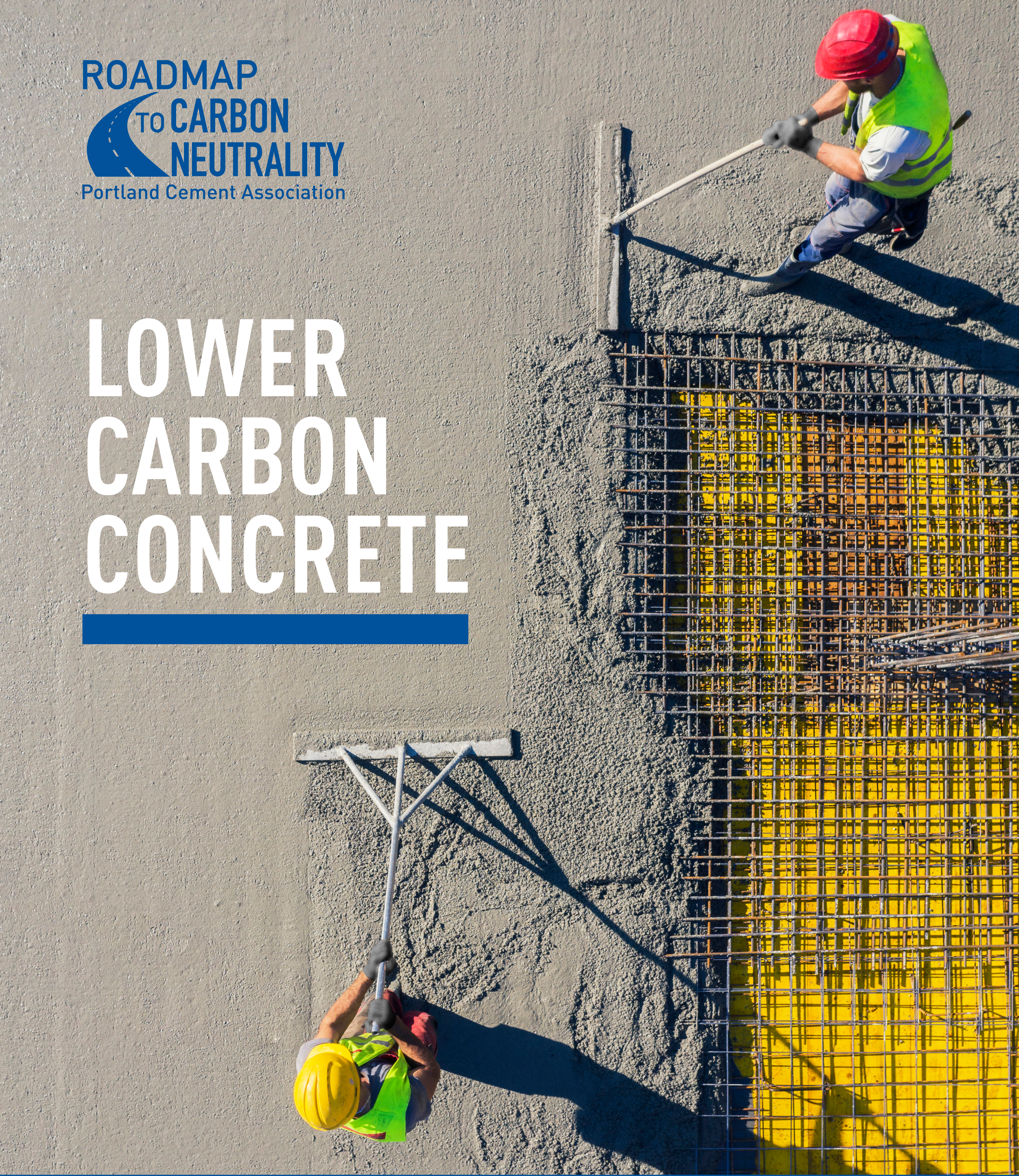

ROADMAP TO CARBON NEUTRALITY
Portland Cement Association

LOWER CARBON CONCRETE

VOLUNTARY GUIDELINES FOR DEVELOPING A PROTOCOL

ROADMAP TO CARBON NEUTRALITY

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CONTENTS

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SCOPE

This document provides design professionals, contractors, code officials, elected representatives, non-governmental organizations, and the public with a framework for developing a lower carbon protocol for concrete.

The voluntary guidelines address the materials, methods and metrics by integrating carbon reduction among all aspects of the built environment. Topics covered include the materials and proportioning of concrete mixtures, considerations during design and construction, and testing and performance criteria for acceptance of concrete.

A protocol developed with this approach is intended to lower the carbon of a concrete project without sacrificing long-term performance characteristics like strength, durability, and resilience while also advancing the circular economy.

The voluntary guidelines are numbered, in bold text; the text that follows is the authors' commentary on the guidelines.

SECTION 1: MATERIALS TO ACHIEVE LOWER CARBON PERFORMANCE

1.1. To the extent practical, locally available materials should be used.

Definitions of a "local" material may vary. It is important to establish a definition appropriate for the specific material and the project location. All other aspects of a material being constant, haul distance will be the final determinant of GWP. However, in some cases materials at a further distance may have an embodied carbon content lower than materials that are closer, and examination of the GWP considering all factors is required. In some cases, there is not a choice of materials and carbon reduction can only be accomplished by optimizing the concrete mixture design to minimize the quantity of material used.

Use life-cycle analysis (LCA) to compare materials and account for transportation emissions. An LCA methodology examines the environmental impacts of a product during each stage: raw material extraction, manufacture, construction, use, disposal, and recycling. Transportation impacts are considered for and in between each stage.

Results of an LCA for a material may be reported on an Environmental Product Declaration (EPD) according to the rules established by the Product Category Rule (PCR) for that class of material. Some LCA and EPD tools quantify the impact of product transportation of products.

When designing concrete mixtures, establish the availability of raw or recycled material throughout the expected duration of the project before final material selection. An inconsistent supply or inadequate reserves may result in a change of materials mid-project. In addition to project delays, this may lead to use of a material that does not meet the desired carbon reduction goals. Long-distance transportation of construction materials should be considered only after local sources of materials have been eliminated as a possibility either due to performance or GWP considerations.

When analyzing locally available materials in comparison to materials requiring long-distance transportation, consider the following questions in the order listed:

1. What is the full range of desired performance characteristics including structural performance, durability, cost, and embodied carbon?
2. Are local materials available that can meet these combined characteristics?
3. Are there recycled materials available?
4. Are the required performance characteristics appropriate?
5. Can the required performance characteristics or the structural design be modified to accommodate use of local materials?
6. What is the Global Warming Potential (GWP) contribution of transporting non-local materials? (consider transportation methods and distance)

1.2. Materials that meet standard specifications should demonstrate lower embodied carbon.

While existing standard specifications don't address GWP, materials meeting these standards may still be used to lower embodied carbon. Because a material meets a standard specification does not mean it has lower embodied carbon.

The properties of a given material needed to achieve a performance requirement are always an important factor when selecting materials. Certain properties can be leveraged to allow the use of less material when compared to alternative materials.

Any analysis of embodied carbon must also consider functional equivalence, as defined by the application and the desired relevant performance properties such as strength, durability, density, workability, placeability, finishability, cracking potential, stiffness, and other such performance properties.

All constituent materials for specific applications should be used appropriately to lower embodied carbon. For example, a concrete mixture without an optimized aggregate gradation may require more total cementitious content as compared to a mixture using an aggregate gradation that has been optimized.

Rely on performance specifications and only specify what is required. Include embodied carbon as its own performance criteria. Carbon budgeting for the whole system or project permits the use of concrete mixtures with higher carbon intensity while still achieving an overall carbon reduction for the project. Section 2.2 discusses carbon budgeting further.

1.3. New or innovative materials for which a standard specification has not been developed should demonstrate similar performance as a material targeted for replacement when used in the same application under the same expected conditions.

Technology and material advancements often outpace standards development. Therefore, novel materials should not be excluded simply because they are not covered by an existing specification. The user should examine sustainability benefits, scalability, and the applicability of available data demonstrating the performance of the innovative material. Data used to document performance should be developed using tests and methodologies demonstrating satisfactory performance through research or field use.

Specifications should permit substitution requests by approval if they meet the owner's objectives.

Consider novel materials for use in non-structural components first as proof of concept prior to broader uses. Attention should be given to the constructability of concrete made using a novel material, or the ease with which it may be used in practice.

Standard test methods used for concrete made with conventional materials may not be suitable for all novel materials. New test methods used for qualifying these materials should be correlated to field performance, demonstrate repeatability, and developed in a consensus-based process.

Many of the current test methods are based on hydraulic clinkers and the boundary conditions of these tests were developed for these specific materials. When current test methods are used for innovative materials, the boundary conditions and assumptions should be carefully reviewed.

Consider the following in decision-making and testing for new or innovative materials:

- Does the new material provide the required performance for the given application?
- What are the limitations of the new material, including consistency and supply?
- How much field experience with the new material exists and is the field experience consistent?
- Can the material be used in non-structural conditions?

Understand and, where appropriate, use mechanistically based modeling, artificial intelligence, or other technological advances to predict the performance of new materials. It is generally good practice to validate a model using data obtained from separate laboratory and/or field experiments.

A higher degree of quality control may be necessary for innovative materials. The carbon reduction benefits of an innovative material cannot be achieved if the concrete produced using that material does not meet the required durability or strength performance. Quality control is discussed in more detail in Section 2.4.

1.4. Specific materials requirements of strength, durability, sustainability, and resiliency for a given service life are defined by the application and exposure requirements.

While strength and durability are addressed with appropriate design codes, minimum code requirements do not always address sustainability or resiliency.

The definition of sustainability extends beyond embodied and operational carbon; it refers to meeting the needs of the present without compromising the needs of future generations. In comparison, resiliency considers whether or not a product or project is responsive to or can overcome vulnerabilities encountered throughout its service life. Something can be sustainable but ultimately, not resilient. For example, a road may be designed using sustainable construction practices and materials, but if it floods regularly, it is not resilient. The reverse is also true: something can be resilient but not sustainable. Pavements designed to airport runway quality but used in residential areas may be resilient but are not sustainable due to the overdesign. Overdesign is not necessary to achieve resilience and is inherently unsustainable. A sustainable, resilient residential road optimizes use of local resources and is designed to be flood resistant and fulfill the needs of the residents. Local materials, overdesign, and optimization are discussed in detail in Sections 1.1, 2.3, and 2.5, respectively.

Durability considerations often support resiliency considerations, and vice versa. Beyond durability, resiliency can also be enhanced with robustness and redundancies. Owner requirements for durability and resilience may exceed the minimum requirements in building codes and standard specifications.

Material choices should intentionally address strength, durability, sustainability, and resiliency simultaneously.

SECTION 2: METHODS TO ACHIEVE LOWER CARBON CONCRETE

2.1. Communication and Consistency.

It is critical to evaluate, address, and communicate embodied carbon reduction goals and strategies during the early stages of conceptualization and design, where the most significant opportunities for reduction exist. Figure 1 illustrates the critical nature of communication in the planning and design phase.

The traditional design-bid-build project delivery model limits opportunities to reduce embodied carbon during planning and design, when there is the greatest opportunity to affect reductions through engagement with contractors and material suppliers. Alternate delivery methods such as design-build can facilitate this contractor engagement at the early project stages.

Meeting carbon reduction goals necessitates a collaborative effort. Ideally, all parties are involved in establishing realistic goals at the outset and tracking progress throughout the project.

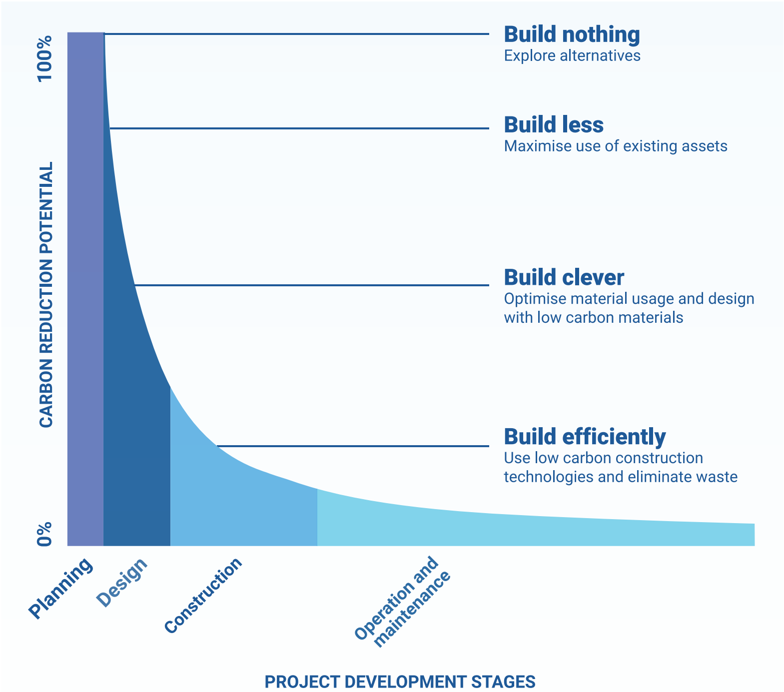

Figure 1: Opportunities to reduce embodied carbon from stage of design process (World Green Building Council 2019).

a. **Set clear expectations for communication and use consistent approaches among project team participants.**

Consistent approaches and regular communication provide clear expectations, encourage accountability, and reduce risks by asking the following:

- What is the goal?
- Why is it important?
- Who is responsible?
- What needs to be achieved (and by when)?

Expectations should be established early and communicated often. Ideally, regular communication aligns with the construction timeline. Ensure timely identification of problems and communicate both the problem and the resolutions to ensure lessons are learned.

b. **Lessons learned from pilot projects should be considered.**

Like the research required for building circularity, all decision-makers should assess current best practices and results from pilot projects or other innovative endeavors.

Early adopters often receive recognition for setting the bar higher with their innovations. Look for project examples and case studies from award winners.

Government agencies require publishing lessons learned (case studies, and regular project reporting) for projects using grants or other government funds. Government agencies use funds to prompt innovation with the expectation that future best practices and projects can learn from pilot projects. Examples and other resources are listed in the references.

c. **Opportunities for integrative design through collaboration with procurement and design teams should be identified.**

As with risk-sharing, some project models lend themselves better to collaborative decision-making.

More realistic goals and plans may be established when early design conversations include materials suppliers and contractors.

Early and regular communication among a broader range of project participants (particularly those that are traditionally involved later in the project) can prevent design conflicts and improve efficiencies. Design charrettes may be used to create collaborative environments and promote information sharing. Early collaboration helps participants engage in system-wide thinking rather than focusing on their own individual project elements.

While interdisciplinary collaboration is not always practical with every project delivery method, project team members should be sensitive to gaps in perspective and expertise. This awareness informs the big picture.

d. **Pre-bid open houses for government-owned/led projects should be encouraged and facilitated.**

Because government-owned/led projects typically limit pre-bid communications with contractors, pre-bid open houses provide an opportunity for earlier engagement and collaboration.

As with any new practice, owners may face resistance from designers and contractors preferring traditional means, method, or materials. It's important for all parties to understand the benefits of new practices, and in this case, how pre-bid open houses may be used to improve quality, incentivize innovation, and reduce risk.

e. **Deployment of comprehensive open-source databases and low-carbon references should be supported.**

Transparency in source data will be key to the usefulness of such databases and references.

Likewise, transparency in vetting low-carbon references ensures users of the reliability, credibility, and appropriateness of the references.

When building and using databases, it's important to consider both the data quality (from producers) and its most appropriate use (by owners, engineers, contractors). More data isn't necessarily better data.

Detailed data and its analysis drive more granular industry-average data into regional, and product-based sub-categories. EPDs are sources of transparent, third-party verified data at all levels, from the product/plant level, to regional averages, to national averages. Until concrete EPDs move beyond the impacts associated with A1-A3 life cycle stages (production stages, or upfront "embodied carbon"), a whole life cycle analysis is required to compare one material against another. Additionally, when comparing EPDs within a database, ensure products are functionally equivalent.

f. **Decision-makers across the entire value chain and throughout a project's life cycle should be educated.**

   Inform decision-makers on strategies to reduce the embodied carbon in concrete mixtures and what regionally appropriate methods have been successfully used in the past. A benefit of early and regular communication and collaboration is increased awareness of project goals and their benefits. With better awareness across the entire value chain, there is less risk of decision-makers using faulty assumptions that inhibit progress. This includes, for example, informing decision-makers on strategies that reduce the embodied carbon in concrete mixtures.

2.2. Use published guidance based on performance requirements.

This section addresses the use of published guidance to achieve lower carbon concrete that meets the performance requirements for a given project or application. It extends to the use of guides, specifications, codes, and other frameworks that share the same goal.

Delivering concrete so that it can be used in construction to meet its intended performance is imperative. Performance specifications that focus on fresh and hardened concrete properties and minimizing prescriptive methods for construction are preferred over prescriptive requirements that specify constituent materials, proportions, or limits. In general, specifications that include minimum cement contents, limits on SCMs, limits on w/cm, or specific products restrict flexibility and innovation and may restrict viable pathways to achieve carbon reductions. They can also lead to over-design of mixtures, resulting in an unnecessarily higher carbon footprint. Performance specifications should be adopted and implemented (including appropriate testing). Table 1 in the Appendix lists examples of performance specifications and their applications.

Performance considerations include more than strength. They also include other mechanical and durability-related properties. Exposure conditions should be taken into account when determining appropriate performance measures. Performance requirements provide more flexibility than prescriptive requirements in achieving the objectives of lower embodied carbon. Specifying requirements to achieve properties at later ages often helps reduce embodied carbon content.

Below is a list of common performance characteristics for concrete. This list is not intended to be exhaustive and should also include fresh concrete properties, rate of strength development, and thermal properties, when assessing low carbon mixtures. While the current tests may not be applicable to innovative or novel materials, they may be required to ensure the performance characteristics for a given application.

Performance characteristics may include:

- Mechanical performance
- Dimensional stability
- Transport and corrosion
- Freeze-thaw resistance
- Resistance to chemical attack
- Fire resistance
- Thermal performance
- Resistance to sulfate attack and alkali-aggregate reactions

A wide variety of standard testing methods are available through ASTM, CSA, and others.

a. Performance specifications should be adopted and implemented.

Performance specifications define a needed outcome without detailing the composition of products used in construction. In a performance specification for concrete, the responsibility shifts to the producer to achieve the specified performance using industry-accepted standard test methods and defined acceptance criteria. This also requires closer cooperation between the producer and contractor. Conversely, in a prescriptive specification, if the mixture is delivered as prescribed but an intended performance characteristic is not achieved, the specifier is considered to be responsible.

Project specifications should be reviewed to identify prescriptive limits on the composition of concrete mixtures, and to implement alternative specification provisions based on performance. Common prescriptive limitations include limits on type and quantity of cementitious materials, type and quantity of supplementary cementitious materials, maximum w/cm, or limitations on the characteristics and grading of aggregates that can be used.

Performance specifications allow for innovation of concrete mixture designs to ensure performance requirements are met while providing lower carbon concrete. Performance specifications allow for flexibility in paste composition and volume in concrete (for example, lower paste content, cement content, and/or lower clinker content cements), leading to lower carbon emissions and improved concrete performance (such as lower shrinkage and lower permeability).

By contrast, prescriptive specifications tend to limit the ability to optimize cement and supplementary cementitious material (SCM) content, leading to over-design (where actual properties are greater than the designed intent), adverse performance impacts (increased permeability, cracking, etc.), and increased carbon footprint.

b. Performance specifications should meet the intent of applicable codes and standards.

Some local jurisdictions set their own requirements rather than follow those recommended in national standards.

Although an appropriate performance specification may be developed, be prepared to adjust to requirements of local codes and regulations. When adopting performance specifications, ensure alignment with other cited specifications that may be prescriptive: such as requiring temperature control with low SCM limits.

When existing specifications are not kept current, it hinders the use of low carbon materials. Further hindrance stems from mandating materials or processes not yet at scale. In the event specifications do not permit use of low carbon materials, allowances or waivers may be required.

c. **Specifications should allow material and test method substitutions that demonstrate equivalent performance.**

Specifications should encourage innovation. One way to do this is to allow substitution requests with approval.

Specifications should consider more than one performance characteristic and set requirements for demonstrating equivalent performance. For example, rather than just specifying compressive strength, one may consider the rate of strength development with early-age strength for constructability and later-age strengths for ultimate acceptance. Similarly, transport properties including rapid chloride penetrability tests (RCPT) or resistivity criteria in lieu of w/cm limits may be as critical or more critical than strength in some applications. Further, ultimate acceptance may be based on later age properties beyond the typical 28-day test age, such as 56-day testing, to provide time for the SCMs to react.

Considering a range of test methods may be necessary. Likewise, current test methods may need adjustments. For example, test specimens may mean specimens are demolded later and conditioned or cured for longer periods than existing standards. Also use new tools and modeling techniques to allow and accept new materials.

For example, maturity and/or temperature-matched curing (temperature profiles from in-situ sensors) or in-place strength tests provide a better measure of strength development in a structure instead of standard-cured cylinders cured in a laboratory. SCM concretes can often develop higher early-age strength than indicated by lab cylinder tests.

d. **Where consensus-based standard tests do not exist, alternative test methods that support novel materials' procurement should be considered.**

To enhance flexibility and increase innovation, alternative test methods should be considered where appropriate. Existing standards or practices may not align or keep up with the pace of industry innovation. Examples include:

- ACI 211 for mixture proportioning may not be relevant to achieve low carbon concrete.

- Rapid assessment of chloride diffusion using the NORDTEST NTBuild 492 rapid chloride migration test or AASHTO T 357 rapid migration test may be preferred over current ASTM test procedures.
- In the context of materials for structures governed by the International Code Council, ICC acceptance criteria (AC) 529 is available.

2.3. Optimization Strategies

a. Develop a total carbon budget for the entire project and assign individual carbon targets within that overall budget.

A carbon budget helps set emissions reduction targets for a given project. This helps reduce carbon in concrete construction projects and enables collaboration on projects to achieve project goals. For example, the new ACI CODE 323 - Low-Carbon Concrete provides for project-wide GWP performance targets using a carbon budget approach.

The process generally consists of performing the concrete volume takeoff with various strength/exposure classes, identifying targets and typical mixtures and mixture designs with lower GWP, calculating the proposed scenarios, and proposing a project budget that meets overall carbon reduction goals.

There are industry documents available that help explain concrete carbon project budgets and also provide case studies with examples (NRMCA Concrete Carbon tool, the Canadian Ready Mixed Concrete Association (CRMCA) Concrete Carbon - A Guideline for Specifying Low Carbon Ready Mixed Concrete in Canada.)

Compliance reporting should encourage optimization of whole systems rather than setting limits on individual concrete mixtures.

Ideally, the total carbon budget LCA should include operational emissions and account for energy savings attributable to the thermal mass of concrete. This can assist with concrete system selection to optimize envelope area and volume of conditioned space.

b. Develop a checklist, flowchart, or use optimization tools to facilitate material selection and decision-making.

Checklists and flowcharts are intended to aid the decision-making process. In the simplest forms, these aids support institutional knowledge so that decision-makers don't reinvent the wheel with every material selection. As internal documents (as opposed to formal standards), it may be easier for these aids to be updated and keep pace with innovation.

While examples from FHWA, ASTM, and other organizations may exist, the most useful checklist or flowchart will be application-specific and sensitive to the needs of the project and its decision-makers.

c. **All sustainability impacts should be evaluated throughout the entire life cycle.**

Building life cycle stages are defined by ISO 21930 standard, as illustrated in Figure 2. Current standards for materials tend to prioritize manufacturing. For example, PCRs require evaluation of cradle to gate life-cycle stages (A1 – A3) , while not accounting for transportation to project (A4), construction and installation (A5), use (B1-B7), end-of-life (C1-C4) and beyond life (D). Decision makers should use life cycle analysis throughout the entire project (cradle to grave). Given the number of changes encountered throughout the construction phase, it's important to track and evaluate those changes using the LCA.

LCAs can be used as a tradeoff analysis. For example, examining higher CO_2 materials that last longer and have better performance, or alternatively, using higher CO_2 material but less of it. Individual carbon targets are only acceptable when taken within the context of an overall project carbon budget.

While current priorities center around global carbon reductions, and GWP is therefore a focus, all three pillars of sustainability impacts (environmental, economic, social) should be evaluated consistently. Assessing the full scope of impacts, not simply environmental impacts, over the entire life cycle of a product or project provides the more complete, long-term picture of benefits and tradeoffs.

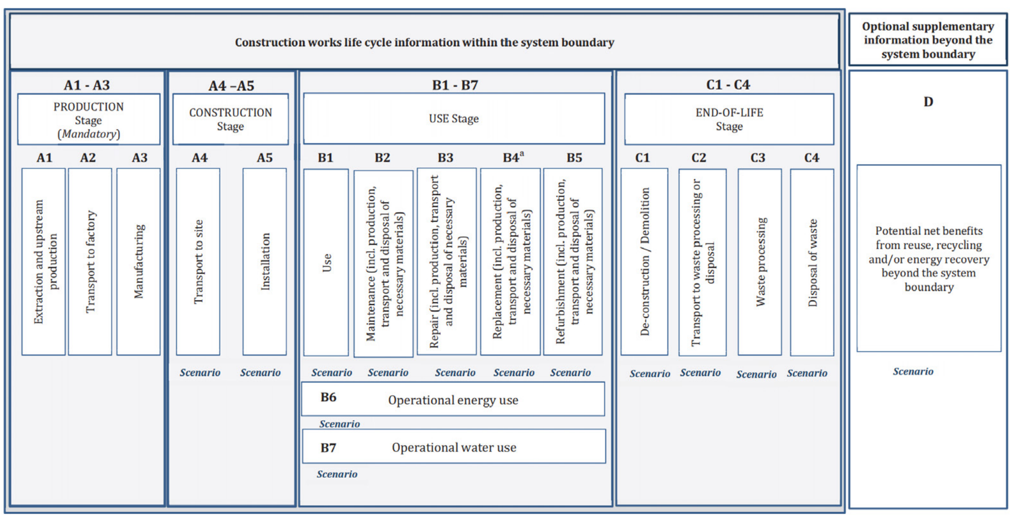

Figure 2: Common four life cycle stages and their information modules (ISO 21930 2017)

d. **Optimize the concrete mixture.**

The following strategies should be used to develop optimized mixtures:

- Select material constituents for optimized workability, strength, durability, resilience, and sustainability.
- Adopting well-graded aggregate combinations to minimize paste content.
- Using admixtures to optimize the fresh and hardened concrete properties and minimize paste content.

- Allowing the use of blended cements, including Type IL, Type IT, and other innovative, lower-carbon cements.
- Allowing for appropriate levels of SCMs to minimize embodied carbon while achieving the desired performance.

Concrete mixture optimization should be a goal at all levels: at the system level, at the project level, at the product level, and down to the individual material component level.

Consider, for example, how cementitious material fineness may influence its workability, water demand, reactivity and necessary final mixture proportions, and balance that with the energy required to obtain a given fineness.

e. **Structural systems should be optimized for structural and life cycle performance.**

    i. **Use LCA through design, construction, use, and end-of-life phases.**
    ii. **Design for purpose and performance over the full life cycle of the system.**
    iii. **Avoid designs that go beyond what is required for the application and exposure conditions.**
    iv. **Define the intended use of the structure and design for the most likely future uses.**
    v. **Design for resiliency with principles that minimize damage, disruption, and economic impact of severe events.**
    vi. **Document design decisions.**
    vii. **Intentionally balance structural and life cycle performance.**

One example of optimizing a structural system is the use of high-strength concrete. High-strength concrete (which may contain higher amounts of cement) used in design could result in smaller elements, flat plate floors, and smaller columns, which in turn reduce weight and permit smaller foundations. Less concrete overall uses fewer resources. Flat plate floors versus column-and-beam systems typically reduce floor-to-floor height by 12 inches (20-inch-deep beams to 8-inch-deep flat plate slab). This reduces the environmental impact of cladding materials by reducing the size of the facade by as much as 10 percent. Where possible, integrate the operational energy into the methodology, as a 10 percent reduction in floor-to-floor height reduces the volume of conditioned air in the building by 10 percent—a direct 10 percent energy savings for both heating and cooling.

2.4. Circularity.

The United Nations Environment Programme notes that circularity builds upon value retention loops as depicted in Figure 3: user-to-user processes where a product or a component remains close to its user and function; user-to-business processes where a product or component is upgraded, and producers are involved again; and business-to-business processes where a product loses its original function. In this way, circularity challenges the current economic model towards a sustainable future and addresses the following:

- Keep materials at the highest possible value along the value chain.
- The entire value chain matters, more than each stage individually.

- All stakeholders are engaged in changing the system.
- Life cycle thinking enables the identification of strategic intervention points.
- Disconnecting natural resource use and environmental impacts from economic activity and human well-being.

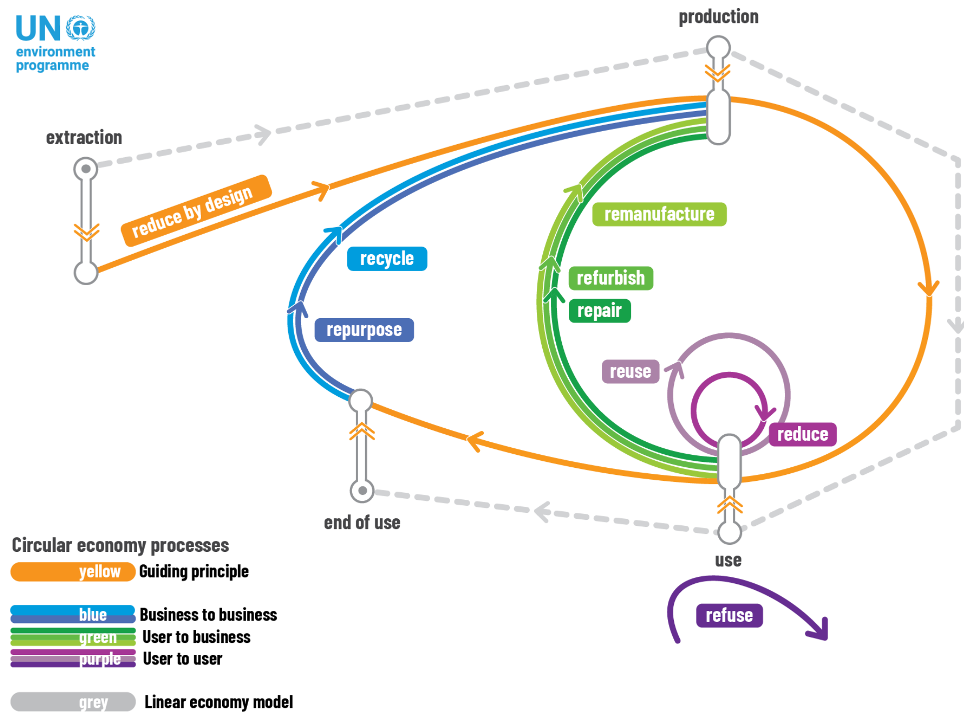

Figure 3: Circularity builds upon value retention loops. (United Nations Environment Programme 2019

Circularity is created in systems, not with individual material suppliers. While an individual material supplier may be able to plan for circularity, it is up to the broader network of decision-makers to use their products and by-products as intended. Circular systems efficiently use resources (including by-products) and require connections among a network of consumers and suppliers.

Current practices allow concrete to play a significant role in building circularity. Production of cement uses alternative fuels including some materials that would otherwise be landfilled. The materials used to manufacture cement include industrial byproducts such as coal ash. Additional recycled materials and industrial byproducts are used in concrete production. At the end of its useful life, concrete can be 100 percent recyclable.

Building circularity necessitates thoughtful planning and pre-designating ideal scenarios for end-of-life. Planning includes looking for opportunities for repurpose, future vertical additions, planning for higher resiliency, and designing for disassembly and reuse. Working past the end of life might include developing an end-of-life-plan for the structure that is incorporated in specifications or building end-of-life into the design.

a. **All aspects of circularity across the full life cycle of the material, the structural system, and the overall project should be considered.**

Significant effort may be required to investigate local opportunities to develop and incorporate circularity. Initial assessments may simply look for the availability/viability of excess resources.

As collaborative partners in systems of circularity, material manufacturers should audit resources used and sent to landfills and seek opportunities for landfilled resources to be beneficially reused. For example, identify ways in which concrete that would otherwise be "returned" to the plant may be used in other applications, whether on the project site or in the local community.

The Sustainable Materials Management program of the U.S. Environmental Protection Agency includes resources for construction and demolition (C&D) materials generated during the construction, renovation, and demolition of buildings, roads, and bridges. As circularity becomes more common practice, other information resources will emerge.

b. **At the end of initial use, a decision-making hierarchy that evaluates the implications of replace/repair/reuse and incentivizes the best choice among those options should be used.**

Hierarchies can be established early to inform end-of-life decisions. Such hierarchies make the intended use of the product/project clear without the need for constant communication with the original decision-makers.

Hierarchies should delineate commonly understood best practices for replacing, repairing, or reusing resources. Simplicity and ease of implementation may be enough incentive for future decision-makers to use hierarchies, as the benefits and savings will be quickly realized. For example, how might panels be reused vs. their recycled value; or what are the implications of deconstruction vs. reuse?

Such decision-making hierarchies ensure that circularity considerations made in the design phase are most likely carried forward.

When addressed in the design/construction phase, these hierarchies help future decision-makers answer questions such as:

- When should an element be repaired vs. replaced?
- What from the original system may be reused?
- What necessitates new construction, and have all reusable elements been identified?
- For elements that cannot be reused, how can they be recycled?
- What are the potential tradeoffs?

c. **Opportunities for beneficial use of by-products and waste materials, including developing screening criteria for by-products and waste materials should be identified and incentivized.**

Part of the research necessary for each participant in a circular network includes looking for opportunities for reuse. Decision-makers at the project level should understand system requirements and the local availability of possible alternatives. Industry participants should also understand their own internal systems, where there are excess resources viable for use. Accounting for materials sent to landfill should not be proprietary information; availability of this information opens opportunities for innovation for how a material might be used if its availability is known.

Examples of identified by-products include:

- SCMs
- non-potable water
- returned concrete
- ground glass
- recycled concrete aggregate

Also notable, a significant percentage of reinforcing steel is manufactured by recycling scrap steel.

d. **Feasible end-of-life solutions should be included in life-cycle analyses with options including:**

i. **Repurposing or alternative uses of structure, including novel end-use applications;**
ii. **Possible future additions;**
iii. **Increased resiliency requirements due to climate change; and**
iv. **Design for disassembly or component salvage.**

The intention of a life-cycle assessment is to gain a realistic understanding of a project's impacts. As with any budgeting exercise, the more alternatives evaluated, the more realistic the predictions may be. The purpose of an LCA is not to identify a single definitive answer of carbon savings over 100 years, for example. Rather, the purpose of an LCA is to identify all potential options that can lead to fewer adverse impacts and use the information to make better decisions throughout the design, construction, and operations phases. Without including feasible end-of-life solutions, the LCA only provides part of the picture.

2.5. Quality Control.

Achieving lower carbon concrete requires increased quality control. Increased quality control also leads to reduced overdesign. Reduced overdesign prompts more efficient use of materials and fewer performance problems, such as cracking, higher in-place concrete temperatures, shrinkage, creep, and alkali-silica reaction. With improved durability, infrastructure service lives are extended and maintenance activities are reduced, reducing materials required for repair and replacement.

When using new materials, contractors, and producers should understand and communicate any tradeoffs, such as changes in water demand that may affect placing, finishing, strength, setting time, etc., to manage expectations and adjust handling, placing, and curing procedures.

Specifications that are more stringent than code requirements may unintentionally lead to a higher GWP.

Testing in accordance with standards is critical, and adherence to standards avoids strength reductions. Certifications of the manufacturing facilities (plants), mixer trucks, and personnel who proportion the mixtures is a must. The same can be stated for installers, the owner's independent testing laboratories, and their personnel.

a. **Pre-qualification testing and acceptance criteria should be developed that facilitate the use of concrete with lower overall embodied carbon.**

   Appropriate pre-qualification testing and acceptance criteria that consider including later test ages to accommodate a slower rate of strength gain should be developed. Requiring lower early-age strengths based on when and how much strength is needed helps optimize the concrete design.

   Trial batches and mock-ups or demonstration placements are good practice and are often required, particularly when making changes in constituent materials or when evaluating concrete with innovative materials and special concrete performance requirements to ensure that quality is maintained as mixtures are scaled up and are placed with the intended placement methods. Trial batches and demonstration placements should be assessed prior to construction so that necessary adjustments may be made. Mock-ups or demonstration placements are also useful to familiarize placing crews with potential changes in handling, finishing, and curing that may result from use of lower-carbon concretes.

   Early age strengths are usually set by the contractor, not the Engineer of Record, to meet schedule. The owner should consider delayed delivery or acceleration elsewhere in the schedule as an alternative to achieve lower CO_2.

b. **Incentivize the acceptance of end products rather than their constituent materials or individual components (concrete vs. cements, aggregates, and admixtures).**

   As discussed in section 2.2, performance specifications are the preferred means for accepting end products rather than prescriptive specifications that establish constituent material requirements and proportions and limit innovation. Incentives can spur innovation and collaboration that support low carbon and extend design service life.

c. **Risks involved in new or innovative materials or systems should be identified to determine the party responsible for those risks and how those risks could be addressed.**

   Expanded collaboration and early engagement from all stakeholders reduces overall risk and allows better opportunities for risk-sharing. Some project models including public-private partnerships, and construction manager at-risk, have inherent risk-sharing paradigms and these models should be used to leverage innovative materials or systems. See Section 2.6 for discussion of the use of incentives to reward and de-risk innovative materials and approaches.

2.6. Incentives that use a holistic approach, balancing project requirements and risks associated with novel materials or innovative design approaches, should be created.

Incentives may be found in state/local government initiatives. When establishing incentives (or modeling new initiatives from existing ones), it's important to use a holistic approach. This means tradeoffs are considered alongside benefits and better inform priorities.

As an example of a government incentive for new construction: As of spring 2024, IRA funds can be used for reimbursement by the FHWA of incremental costs or incentive payout of 2 percent of material costs on funded projects for state DOTs. Reimbursable incremental costs can include studies to benchmark the GWP of materials available locally for DOT projects and set appropriate targets for GWP reductions.

Incentives can also be used at later stages of a project's life cycle. For example, some municipalities offer funds for reuse of certain structural elements, tied to demolition permits.

Agencies seeking to offer incentives for lower carbon concrete may look to other incentive models that have been used to promote the use of innovative materials and practices (for example, incentives to use optimized aggregate grading in mixture designs), for lessons on what has and has not worked well in the past.

Incentives may not necessarily be financial. As an example, some state DOTs have reduced or eliminated minimum cement contents for contractors willing to use optimized aggregate gradations on paving projects. While lower carbon concrete would not have been the initial objective of these incentives and alternate specifications (the objective was the adoption of PEM program elements), it would be an additional benefit if contractors are using paving mixtures successfully with lower cementitious materials content.

SECTION 3: METRICS

3.1. Any metric used should allow for informed decision-making for all alternatives.

Metrics should enable owners, agencies, and designers to collaborate with contractors and material suppliers to make informed decisions about alternatives. Knowing which alternatives are within budget helps, as does knowing how much carbon will result from one alternative versus another.

Materials EPDs should not be compared across different PCRs. Product category rules provide category-specific guidance for estimating and reporting product life cycle environmental impacts, typically in the form of EPDs and product carbon footprints. Product Category Rules that establish product metrics emphasize the value of "declared" or "functional" units to support like-to-like comparisons. Differences in the general requirements (product category definition, reporting format) and LCA methodology (system boundaries, inventory analysis, allocation rules, etc.) diminish the comparability of products.

Concrete is often selected due to its ability to provide a long service life. Thus, metrics based solely on cradle-to-gate are less useful than metrics that consider the cradle-to-grave or cradle-to-cradle life cycle.

Metrics should be identified that address goals at both the project and product levels, and in some cases project goals can inform product-level metrics. For instance, once project goals are identified ensure the selected materials can achieve the project goal-based performance requirements of that material.

Metrics can be used for a range of reasons, such as:

- Measuring progress toward goals
- Comparing options,
- Establishing targets for the products using a project-wide carbon budget.

a. **Metrics should be application or exposure-specific and not solely based on compressive strength and constructability.**

Just as the selection of a material is application-specific, the metrics used to determine success should also be application-specific. For example, specialty types of concrete like grout, flowable fill, cell fill, pervious concrete, and lightweight aggregate concrete, will have very different GWP for a given strength compared to conventional concrete. Application-specific metrics may also need to include air entrainment, pumpability, finishability, or early strength.

Currently, GWP averages are often based on the strength class of concrete. While this may be the best available data, it fails to account for the environment in which the concrete will be exposed. Concrete in more severe environments (such as salt water or water treatment facilities) may benefit from binders that provide enhanced transport properties that will provide longer service than concrete in a less severe environment (concrete on the interior of a building). Another good example is air-entrained concrete, which typically requires more cement and lower w/cm compared to a non-air entrained concrete with the same strength.

An example of a performance-based standard specification is AASHTO R 101, which enables specific transport properties to be measured using a resistivity test rather than assuming it is based on a prescriptive property like w/cm. This enables the end user to consider performance mixtures made using SCM with a lower carbon footprint that may not be possible with prescriptive w/cm specifications.

b. **Metrics should be simple, concise, transparent, and understandable.**

Transparency in the metrics is key to providing a clear understanding of the factors considered, enables the most direct comparisons of alternative solutions, and builds confidence in the process.

c. **Metrics should focus on the project's primary determinants within the overall carbon budget.**

Every project has a range of stakeholders, and multiple factors are important to each group. Stakeholders should cooperatively determine which project variables are selected along with the prioritization and weight of those variables. When prioritizing carbon reductions, likely primary determinants include GWP, service life, carbon budget, resilience, etc.

Five main factors—GWP 100 (global warming potential of greenhouse gases over 100 years), ozone depletion potential, acidification potential, eutrophication potential, smog formation potential—are associated with the environmental impacts of manufacturing a product on the planet's temperature and air and water quality.

d. **Avoid confusing the measurement with the unit of measure.**

Prioritize identifying appropriate measurements rather than focusing solely on the ideal unit of measure.

e. **Metrics extend beyond a project's primary determinants to other factors that are important to stakeholders.**

The list of possible metrics is endless. Not everything that can be measured is important. Not everything of interest is currently measured. At the same time, some current metrics are no longer appropriate because they are outdated. The bottom line is: if something is important and having more data supports better decision-making, measure it.

3.2. Metrics and measurement technologies are constantly evolving.

Evolving metrics means routinely assessing what new determinants need to be measured (and how to measure them) and also identifying metrics that have served their purpose, no longer apply, and should be "sunset."

a. **Comparisons can only be made by considering all aspects of the product, the project, the industry, the region, and/or the available network and the like.**

Appropriate comparisons support industry consistency and help avoid greenwashing, which is detrimental to efforts. Appropriate comparisons should include dates of measurements and/or expiry dates.

Once a metric is chosen, it's important to use that same metric so that progress can be reported on a consistent "apples to apples" basis. Metric reporting should also include answers to the questions:

- Where is the project geographically?
- What is the specific project application?
- What is the expected life of the project?
- Whose project specifications were used in the design of the project and what drove that choice?
- Were other lower carbon alternatives considered?

b. **Validate data quality continuously.**

   Continuous data validation is important because it supports data accuracy, consistency, and completeness.

   Data may be validated manually and may be supported by spreadsheet software or simple validation software. More sophisticated and specialized software may be required for continuous data validation.

   Data validation and using credible data (including accuracy, precision and bias, proficiency testing, etc.) lends transparency to the process of setting metrics and making appropriate comparisons.

   Credible data refers to the completeness and accuracy of source data. Credible data comes from reputable, transparent, and current sources. The use of independent, accredited testing laboratories is encouraged. Government data and peer-reviewed academic journals are examples of generally credible data sources. Credible sources are transparent in how measurements were completed and use vetted or standardized processes.

c. **Periodically review measurement goals.**

   Metric revisions should consider: how long a given metric has been tracked; the availability of additional data or data collection strategies (what might new information contribute?); and whether a given metric still aligns with the established goal.

d. **Target measurement goals to "push the envelope".**

   What is considered high strength concrete has changed as concrete strengths have increased. Likewise, with advances in technology, what's considered "lower carbon" may not be considered "lower carbon" by 2050.

   By 2050 all concrete may meet what we consider today as "low carbon," so targeting a certain percentage of that may not be the correct exercise.

e. **Metrics should be reported within an appropriate context.**

   It's not enough to report sample size, population size, precision, and bias. Cement EPDs, for example, refer to "technological, temporal, and geographical representativeness." Users may find that the NIST engineering statistics handbook provides a more detailed approach to assess data quality.

3.3. Metrics should make appropriate use of LCA.

Generally, LCAs help assess impacts across several impact categories beyond carbon intensity (or more commonly GWP), including energy use, ozone depletion, or eutrophication. However, what most practitioners in the low carbon space are focused on is GWP. In the context of metrics, LCA is needed to distinguish where the biggest reduction potentials in environmental impacts lie.

LCA (including all phases across the entire life cycle) allows practitioners to identify and then focus on the most impactful reductions and identify the greatest roadblocks to future reductions.

Guidance related to proper conduct of LCA can be found in ISO guidelines. ISO 21931 addresses sustainability within the built environment including buildings and civil works. ISO 14040 and ISO 14044 detail the principles and framework for the LCA process. It is important that metrics developed using LCA be performed in a consistent and transparent manner.

Another consideration is the timing of the LCA. An LCA should be completed not just at the beginning of a project but revisited whenever a decision that impacts future spending or performance is being made such as during maintenance or rehabilitation activities. A life-cycle cost analysis (LCCA) estimates the cost impacts over the intended service life. The LCCA (and LCA) should be developed for a project and revisited throughout service life to ensure proper maintenance and identification of reuse opportunities.

a. **Metrics should report both operational and embodied carbon.**

   Embodied impacts are reasonably well established, and reductions can be readily monitored and implemented. This leads to pathways that are easily navigated and calculated and result in immediate reductions in environmental impacts.

   A variety of tools for estimating embodied carbon emissions of concrete are readily available online, including:

   - National Ready Mixed Concrete Association (https://nrmca.climateearth.com/)
   - Slag Cement Association (https://www.slagcement.org/lca-calculator)
   - Circular Ecology (https://circularecology.com/concrete-embodied-carbon-footprint-calculator.html)
   - WAP Sustainability Consulting (https://thetaepd.com/signup/concrete)
   - CPTech Center (Reducing the Cradle-to-Gate Embodied Carbon Emissions of Paving Concrete)
   - Tally LCA application (www.choosetally.com)
   - Carbon Leadership Forum (https://carbonleadershipforum.org/ec3-tool/)
   - MIT Concrete Sustainability Hub (https://cshub.mit.edu/whole-life-cycle-carbon-uptake-tool/)
   - OneClick LCA (https://oneclicklca.com/en-us/)

   However, focusing solely on embodied impacts can lead to short-term reductions at the expense of long-term improvements in environmental performance. Evaluating all life cycle stages is required to determine where improvements and reductions can be made with asset management and use. With many types of infrastructure, the operational, use, maintenance, and rehabilitation can significantly outweigh the embodied impacts. Thus, it is critical to evaluate these phases, even with the inherent unknowns and uncertainty that accompany evaluating future activities, to ensure that the most impactful reductions can be considered.

b. **Metrics should be appropriately reported as either Scope 1, Scope 2, or Scope 3 emissions.**

The three scopes are a way of categorizing the different types of greenhouse gas emissions created by a company, its suppliers and its customers.

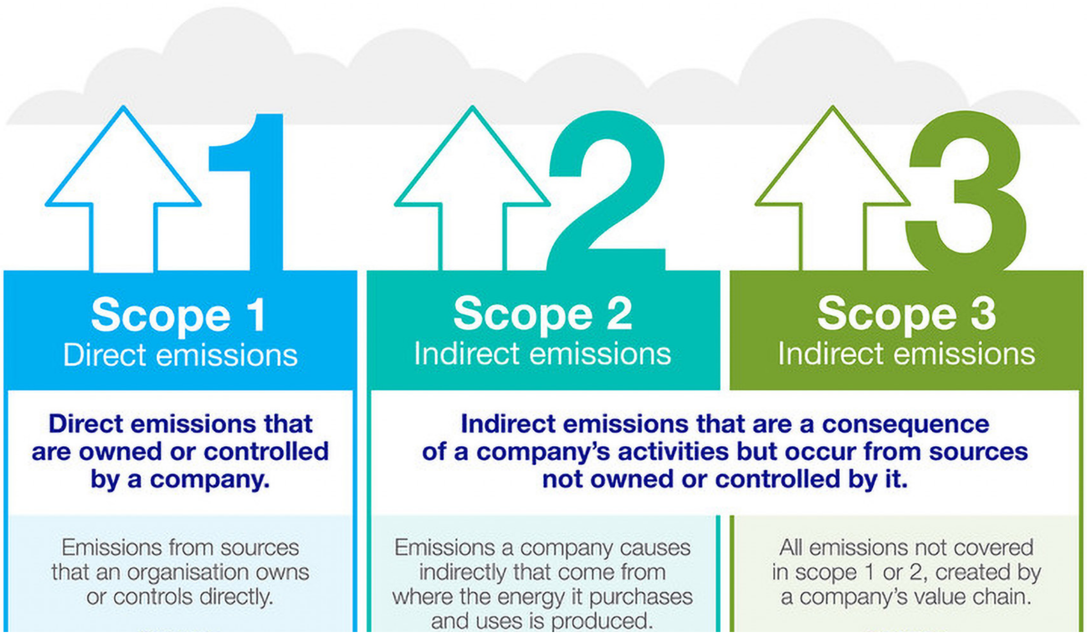

Figure 4: Scope 1, Scope 2, and Scope 3 categorize greenhouse gas emissions. (NationalGrid 2024)

Proper allocation of reductions is necessary to ensure that reductions are not attributed to multiple areas. This is well noted in the guidelines for performing life-cycle assessment as laid out by ISO.

An example is the use phase impacts of pavements. The use phase impacts can include the interactions between the pavement and vehicles traversing the pavement. To ensure that impacts are not double counted, the impacts need to be allocated appropriately to determine what is attributed to the vehicle operations itself and what can be attributed to the pavement as excess fuel consumption and environmental impacts associated with roughness, structure, and texture.

Looking at a single segment of the life cycle omits critical parts.

c. **The impact of carbon should be distributed across the entire life cycle.**

Carbon can be reduced both at the time of construction and over the life of the structure. Simply selecting a material based on its cradle-to-gate embodied carbon may not provide the optimal result for the life of the structure. Solutions that avoid or minimize repair and replacement can result in improved performance over the life cycle of the structure. An historic example of distributing carbon across the entire life cycle is exemplified by the Pentagon building. Initially pitched as a temporary structure, the 435,000 cubic yards of concrete, 43,000 tons of steel, and 680,000 tons of sand and gravel used to construct the building nearly 100 years ago are still in full use today. The embodied carbon of those materials is a fixed amount with continually diminishing impacts when distributed across an extended service life, such as when the temporary Pentagon became the military's permanent command center following World War II.

3.4. Metrics should be reported using a checklist or scorecard format.

Examples of scorecards can be found in many green rating systems that quantify sustainability in the built environment. These rating systems, or frameworks, help define what a sustainable project in the built environment is – from how it is conceptualized to how it is designed and ultimately constructed and operated.

Examples include LEED, Envision, Green Roads, Green Globes, and Living Building Challenge.

A commonality among scorecards is brevity (1-2 pages) and scan-ability. Checklists should provide a snapshot view of key features and shortfalls. Analogous to the need for valid and credible data, checklists should enhance transparency.

a. **Metrics should highlight improvements at all levels.**

"All levels" means we use metrics to highlight improvements across users, across products, and across applications. The goal is to incentivize everyone from "beginner" to "novice" as well as from "top tier" to "best in class."

b. **Checklists or scorecards should be clear and concise.**

It's important for users to see 'at a glance' the metric that's being reported and its place in comparison to all reported metrics and a rough assessment based on that reporting. Simple scorecards provide an excellent opportunity for this type of reporting. A common consumer example is the Energy Star rating found on appliances. A numeric energy efficiency value is shown on a scale bounded by the most energy-efficient and the least energy-efficient for that particular class of appliance. This visual presentation has the added advantage of avoiding arbitrary boundaries between good, better, and best.

APPENDIX/ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
ASTM	American Society for Testing Materials
CRMCA	Canadian Ready-Mixed Concrete Association
CSA	Canadian Standards Association
DOT	Department of Transportation
EPD	Environmental Product Declaration
FHWA	Federal Highway Administration
GWP	Global Warming Potential
IRA	Inflation Reduction Act
LCA	life-cycle assessment
LCCA	life-cycle cost analysis
NIST	National Institute of Standards and Technology
NRMCA	National Ready-Mixed Concrete Association
PCA	Portland Cement Association
PCR	Product Category Rule
PEM	Performance Engineered Mixtures
RCPT	Rapid Chloride Penetration Testing
SCM	Supplementary Cementitious Material
UNEP	United Nations Environment Programme
US EPA	United States Environmental Protection Agency
w/cm	water to cementitious materials ratio

APPENDIX/GLOSSARY

Absolute emissions
All CO_2 emissions generated at a plant.

Acidification potential
Describes the acidifying effect of substances in water and soil. Acidification can occur when substances such as carbon dioxide dissolve in water and lower the ph levels, increasing the acidity of the water. In LCA, this term refers to the local effects of acidification.

By-product
Co-product from a process that is incidental or not intentionally produced and which cannot be avoided.

Calcination
The process of thermally treating minerals to decompose carbonates from ore. Calcination is the first step in a series of complex chemical and physical changes required to make cement. Specifically, limestone is "calcined" in high-temperature cement kilns, driving off CO_2 to create the intermediate ingredient, clinker. See also "chemical fact of life."

Carbon neutrality
The principle by which CO_2 emissions resulting from a product or process are offset either by direct CO_2 emissions reductions or through avoided CO_2 emissions.

Carbonation
The natural absorption of ambient CO_2 by concrete over its life cycle or the injection of CO_2 into fresh concrete. See also "concrete as a carbon sink."

Cement
Any material that binds other materials together.

Chemical fact of life
The fact that even if the industry were to eliminate all combustion emissions, the chemical process used to manufacture clinker creates a separate stream of CO_2 emissions. For example, in the U.S., 60 percent of the CO_2 generated by cement plants is from a chemical reaction called calcination. Calcination is the chemical fact of life in that it is the first step in a required series of complex chemical and physical changes to make cement. The chemical fact of life is also called "process emissions."

Circular economy
A circular economy is an industrial system that is restorative or regenerative by intention and design. It replaces the end-of-life concept with restoration, shifts toward the use of renewable energy, eliminates the use of toxic chemicals which impair reuse and return to the biosphere, and aims for the elimination of waste through the superior design of materials, products, systems, and business models.

Clinker
An intermediate product created during the cement manufacturing process.

Clinker factor
See "clinker-to-cement" ratio.

Clinker-to-cement ratio
The ratio of clinker to cement; typically expressed as a decimal value. For example, a ton of cement composed of 80 percent clinker would have a clinker-to-cement ratio of 0.80.

CO_2eq
Some gases, including methane and nitrous oxide, contribute to climate change and have an effect greater than that of CO_2. The impact of these gases is measured in terms of "CO_2 equivalent," or units equivalent to the effect of CO_2.

Combustion emissions
Combustion is the chemical reaction using fuel and air (or oxygen) to produce heat and/or light. The major products of fossil fuel combustion include CO_2 and water vapor, along with other emissions.

Concrete
A mixture of cement, aggregate, water, and other additives that. When hardened, it provides a resilient, sustainable building material that also absorbs CO_2

Concrete as a carbon sink
Concrete naturally absorbs CO_2 from the atmosphere. Typically, over its lifetime, concrete that is not buried will absorb about 10 percent of the CO_2 emissions generated in its production.

Co-product
Any of one or more products from the same unit process, but which is not the ultimate end product.

Cradle-to-cradle
An accounting method that considers the product life cycle from raw material extraction (or delivery) to the product's salvage/re-use as an alternative raw material thereby completing the material cycle within the circular economy.

Cradle-to-gate
An accounting method that considers the processing impacts from raw material extraction (or delivery) to final product assembly or shipment.

Cradle-to-grave
An accounting method that considers the processing impacts from raw material extraction (or delivery) to the product's final disposal/salvage/re-use.

Data validation
The process of checking the accuracy and quality of source data before using it. Data validation requires the identification of measurement sources.

Data quality
Characteristics of data that relate to their ability to satisfy stated requirements.

Emissions intensity (or **greenhouse gas intensity**)
A measure of the quantity of CO_2 emitted for a designated unit of energy generation or product production.

Eutrophication potential
Describes the effect of adding nutrients to soil or water, causing certain species to dominate an ecosystem and compromise the survival of other species. An example is when an overgrowth of algae depletes water oxygen levels and kills off fish. Fertilizers are a dominant of eutrophication.

Functional equivalent
Quantified functional requirements and/or technical requirements for a construction works or a construction (part of works) for use as a basis for comparison. Example: pavement designed to carry a given number of equivalent axle service loads per day with resistance to ASR and freeze-thaw exposures in a particular geographic location.

Functional unit
Quantified performance of a product system for use as a reference unit. Example: one lane mile of highway pavement that remains in service for 50 years.

Global warming potential
Index, based on radiative properties of greenhouse gases (GHGs), measuring the radiative forcing following a pulse emission of a unit mass of a given GHG in the present-day atmosphere integrated over a chosen time horizon, relative to that of carbon dioxide (CO_2).

Life cycle
Consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal.

Life cycle assessment
An accounting method to evaluate the energy and environmental impacts of a product from cradle-to-grave.

Life-cycle cost analysis
An accounting method to estimate the cost impacts of a structure or pavement over its service life.

Metric
A system or standard of measurement.

Ozone depletion potential
Describes the degrading effect of substances in the stratosphere on the ozone layer, weakening the ozone layer's ability to prevent excessive ultraviolet radiation from reaching Earth's surface.

Performance specifications
Defines the performance characteristics of the final product and links them to construction, materials, and other items under contractor control.

Process emissions
Emissions from chemical transformation of raw materials and fugitive emissions. The chemical transformation of raw materials often releases greenhouse gases such as CO_2, methane (CH4), and nitrogen oxide (N2O). These processes include iron and steel production, cement production, petrochemical production, and nitric acid production, among others.

Resiliency
The capacity of a community, business, or natural environment to prevent, withstand, respond to, and recover from a disruption.

Smog formation potential
Describes the presence of substances such as carbon monoxide and volatile organic compounds (VOCs) in the atmosphere, forming photochemical smog. Smog is harmful to human health (causing respiratory issues) and ecosystems (deterioration of crops).

Transparency
Open, comprehensive, and understandable presentation of information.

Waste
Substances or objects which the holder intends or is required to dispose of.

APPENDIX/TABLE 1

Examples of Performance Specifications, Standards, and Best Practice Guide

SOURCE	DOCUMENT	TYPE	APPLICATIONS
ASTM	C1157	Cement specification	Concrete
ASTM	C595	Cement specification	Concrete – this document and others have performance attributes and represent an important first step.
FHWA	PRS/PAVERIGID	Specification	Pavements
AASHTO	R 101	Standard	Pavements/bridges (permeability, freeze-thaw, shrinkage, aggregate)
NRMCA	Guide to Specifications to Reducing Embodied Carbon[1] and P2P documents[1]	Guidance	Ready mix (permeability, aggregate grading)
CSA	A23.1/A23.2	Standard	Ready mix (strength, permeability, air voids, aggregate, shrinkage)
fib	Model Code 2020	Model Code	Concrete
ACI	PRC-329, Report on Performance-Based Requirements for Concrete	Committee Report	Cast-in-place building concrete
ACI	CODE-323, Low-Carbon Concrete	Model Code	Cast-in-place concrete (f'_c between 2501 and 8000 psi)
CP Tech	Guide to Reducing the Cradle-to-Gate embodied carbon emissions of Paving Concrete	Guide	

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