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Durability of concrete coupled with life cycle assessment: Review and perspective

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ABSTRACT

Extending the service life of structures is an important strategy to mitigate the environmental impacts, in particular, the global warming potential, of the building sector. As a key factor determining service life, the durability performance of reinforced concrete has been investigated for decades. Yet, durability's impact on the eco-efficiency of materials and structures has not been well realized until the early 2010s. Today, an increasing number of publications focus on concrete durability coupled with life cycle assessment (LCA), an important tool for analyzing eco-efficiency. However, the gap between the two research fields, i.e., durability and LCA, has led to divergent methodologies, which hinders the consensus between studies. To bridge this gap, this review covers the recent advances in durability-based LCA. Three aspects were highlighted: 1) how durability influences the eco-efficiency of cementitious materials; 2) how LCA models these effects; and 3) how we come to more justified results. The review argues the necessity of a unified methodology in this field and identifies the importance of performance-based models in justifying durability-based LCA. Further, a framework grounded on the prescriptive and performance-based design methods was proposed to unify the existing divergent methodologies. This framework will facilitate improving the future engineering codes underlining sustainability.

1. Introduction

Concrete is the most used building material globally and the second most used human-made material only to water [1,2]. As the "glue" of concrete, cement accounts for ~10 wt% of concrete; however, it is responsible for ~70% of the greenhouse gas (GHG) emissions in concrete production [3]. In the global context, approximately 4 Gt of cement is manufactured annually [3–5], producing over 10 billion m^3 of concrete [4] and emitting ~3 Gt of CO_2 to the atmosphere [5]. The cement and concrete industry is now responsible for 5–10% of global anthropogenic CO_2 emissions [2,6,7]. Without any mitigating actions, this number may grow till 2050 due to the global population growth and urbanization [1,3].

Reducing the environmental impacts, in particular, the GHG emissions of the cement and concrete industry has aroused the attention of researchers worldwide. As modeled by the Intergovernmental Panel on Climate Change (IPCC), the 1.5 °C climate goal requires a 65–90% cutdown on the global industrial CO_2 emissions from 2010 to 2050 [8]. For the cement and concrete industry, mitigating strategies, e.g., increased use of supplementary cementitious materials [9–11], optimization of concrete mix design [12–15], are readily deployable with mitigation potentials modeled to be 4–12% [4]. Other techniques that may yield zero net emissions for cement production, e.g., carbon capture and utilization during cement clinkering [16,17], alternative binders as substitutes to Portland cement [2,18–20], still need breakthroughs before large-scale implementation [3]. Yet, to reach the climate goal these breakthrough techniques are also essential [3,21,22].

Extending the service life of structures is an effective strategy for mitigating the environmental impacts of the cement and concrete industry [23,24]. As modeled in Ref. [23], ~14% CO_2 emissions in concrete production can be eliminated by elongating the service life of structures by 50%, suggesting a direct approach to reducing the cement demand in construction. However, the service life of structures in the real world depends on both the need for demolishing and rebuilding, and durability, i.e., the resistance of (reinforced) concrete to all types of aggressive environments [25]. Less durable structures may need maintenance to reach the expected lifetime, resulting in additional cost and materials consumption during structure operation [26,27]. To enhance

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concrete durability, adjustments to the concrete mixture and structural elements (e.g., the thickness of concrete cover over reinforcements) are required. Such adjustments also alter the environmental impacts associated with concrete production and construction [15,28–30]. Thus, in real-world scenarios, durability can play a key role in determining the eco-efficiency of materials and structures [31–34].

Life-cycle assessment (LCA), an important tool of environmental impact analyses, has been widely used for assessing the eco-efficiency of cementitious materials [31,35]. The term "life-cycle" represents all lifetime stages of a product being manufactured, used, and disposed of; however, the system boundary of LCA can be defined according to the aim of the assessment. As the simplest way, the cradle-to-gate boundary can be chosen [36–39], which covers the impacts from raw materials extraction to the end of processing by which a material leaves the gate of a factory. To model the effect of durability performance in LCA, the system boundary can be extended to the end-of-life [34,40]. Maintenance actions and the service life of structures can thus be included. Alternatively, such an effect can also be modeled by modifying the functional unit [41–43]. Yet, the selection of the functional unit, i.e., whether a volume of materials [41,42] or a structural element [43], is still under debate. By now, there is no standard method that couples the durability performance of cementitious materials with LCA. Contradictory results were reported through different methods [43,44].

This review focuses on recent advances in durability-based LCA with a goal to fill the gap between cement and concrete materials science and environmental impact analyses and to provide insights to new methodological frameworks. In Sections 2 and 3, an overview of the design of durable (reinforced) concrete and the calculation of its service life was provided. Both sections addressed basic concepts and mechanisms, helping to understand how these durability-related issues impact the eco-efficiency of cementitious materials and how they can be incorporated into LCA. In Section 4, existing papers regarding durability-based LCA were reviewed. Critiques of the existing methods and perspectives on future works were given in Section 5.

2. Durability-related specifications—the prescriptive design method

The goal of durability design is to ensure that structures can resist the aggressive external environment and maintain its serviceability during the full lifespan. Overall, two schools of methods, i.e., the prescriptive method and the performance-based method, are provided in engineering codes. This section overviews the prescriptive design method. This method includes basically the identification of environmental actions (i.e., the type of aggressiveness) and subsequently the specifications on materials, mixtures, cover thickness, etc. It is assumed that a targeted service life, e.g., 50 or 100 years, can be fulfilled when the specifications are simply met. Thus, this method is also termed "deemed-to-satisfactory" design method.

2.1. Environmental actions

Identifying the governing factor which may interact with and deteriorate (reinforced) concrete structures is an essential process before durability design. Such factors are termed "exposure category" in engineering codes, correlating with the degradation, by different mechanisms, of reinforcement (carbonation and chloride ingress) and concrete (freezing and thawing, chemical attack, alkali-silica reaction (ASR), etc.), see Table 1. Within each category, the environmental action is further divided into different classes by their severity, e.g., the concentration of aggressive ions in the external environment. Durability-related specifications are given based on exposure categories and classes.

Table 1

Exposure categories defined in the U.S., European, and Chinese engineering codes, classified by the degradation mechanism.

	Reinforcement corrosion	Concrete damage
ACI 318-19 [45]	● Corrosion protection	● Freezing and thawing ● Sulfate attack ● Contact with water (ASR involved)
BS EN 206:2013 [46] and GB/T 50476-2019 [47]	● Corrosion by carbonation ● Corrosion by chlorides from seawater ● Corrosion by chlorides from other sources	● Freezing and thawing ● Chemical attack

2.2. Durability-related specifications

The most important durability-related specification in the prescriptive design method is concrete mix proportion, including strength grade, cement (binder) content, and water-to-cement (water-to-binder) ratio, see Table 2. These specifications are based on the fact that concrete with a high strength grade and a low water-to-cement ratio typically has a low permeability; and thus it can be sufficiently resistant to aggressive species from the external environment, i.e., ions (chloride, sulfate, etc.), gases (CO_2), and water [48,49]. For concrete subjected to freezing and thawing, specifications on the air content are also given. In general, the design of durable concrete in a highly aggressive environment means an increased demand for raw materials, either binders or chemical admixtures (e.g., air entraining agents in the freezing and thawing environment), for concrete mixtures.

The Chinese code requires laboratory acceleration tests to verify the performance of concrete in some exposure categories. These requirements include: 1) chloride diffusion coefficient tested by rapid chloride migration tests (similar to NT Build 492 [50]) for the exposure categories related to chlorides, and 2) durability factor by rapid freezing and thawing tests (similar to ASTM C666/C666M – 15 [51]) for the freezing and thawing category.

Another important durability-related specification is the thickness of the concrete cover over reinforcements, as rebar corrosion is the most globally observed field problems in reinforced concrete structures [52–54]. This specification applies to the chloride-bearing environment in the U.S. code, to the three exposure categories related to reinforcement corrosion in the European code, and to all exposure categories in the Chinese code. When designing structural elements (beams, slab, columns, etc.), a thicker concrete cover corresponds to higher materials demands and the associated environmental impacts. The strength grade, mix proportion, and the cover thickness for rebars all affect the eco-efficiency of reinforced concrete elements [15,28,30].

3. Service-life models and performance-based design method

In the performance-based design method, the service life of a structure is no longer "deemed to be satisfied". Instead, it is verified based on the actual performance of reinforced concrete members. To reach this goal, degradation models are usually introduced to predict the materials performance during the full lifespan. Service life is defined as the time period before which the performance falls below a certain limit state. In some cases, probabilistic models can be introduced to assess the reliability of prediction. The performance-based design method based on service-life models can be found in international standards, e.g., ISO 16204 [55], the *fib* Model Code 2010 [56], and *fib* Bulletin 34 [57], being also very well reviewed in Ref. [52]. The focus of this section is to address how the most used service-life models are built based on classic degradation mechanisms.

Table 2
Requirements for durability design (the prescriptive design method). Symbol "✓" denotes requirements applying to all exposure categories, "●" denotes requirements applying to partial exposure categories, and "–" denotes requirements not specified in a code.

	Strength class	Maximum W/C	Minimum cement content	Air content and aggregate size (freezing and thawing)	Type of cement and/or SCM	Chloride content	Minimum cover thickness
ACI 318-19	✓	✓	–	✓	●	●	●
BS EN 206:2013	✓	✓[a]	✓	✓	●	✓[b]	●[c]
GB/T 50476-2019	✓	✓[d]	✓	✓	✓	●	✓

[a] BS EN 206:2013 used the concept of k-value to address the impact of SCMs on concrete durability in different exposure categories.
[b] Chloride content is a general requirement, instead of a durability-related one, in BS EN 206:2013.
[c] Minimum cover thickness is specified in BS EN 1992-1-1:2004.
[d] In GB/T 50476-2008, maximum water-to-binder ratio is specified instead of W/C.

3.1. Carbonation-induced reinforcement corrosion

Carbonation-induced reinforcement corrosion can be divided into two periods: the initiation period which corresponds to the penetration of CO_2 to the surface of reinforcements, and the propagation period which corresponds to the corrosion of reinforcements and the cracking, spalling, and collapse of concrete and structures, see Fig. 1. Both periods are important to a concise service-life prediction. For the latter period, various time-dependent models are available [58] and international consensus have not been reached [55,56,59]. Therefore, this section focuses on the initiation period.

The penetration of CO_2 in concrete applies to the diffusion equation, also known as Fick's laws. Assuming that: 1) diffusion takes place in a semi-infinite medium, 2) the CO_2 concentration on the concrete surface remains constant, and 3) the initial CO_2 concentration in the pore solution is zero, one can come mathematically to the solution of Fick's laws that the penetration distance of any given concentration (e.g., the carbonation front) is proportional to the square root of time [62]. This is the well-known Tuutti's carbonation model (also called the square-root law), see Eq. (1) [60].

$$X = k\sqrt{t} \tag{1}$$

where, X is carbonation depth, and k is the CO_2 diffusion coefficient. As a modification, a weather function describing wet-dry cycles, as well as other environmental conditions, can be incorporated [56], see Eq. (2).

$$X(t) = W(t) \times k \times \sqrt{t} = \left(\frac{t_0}{t}\right)^w \times k \times \sqrt{t} \tag{2}$$

where, $W(t)$ is the weather function, t_0 is the time of reference (measure), and w is a weather exponent depending on the level of wet-dry cycles.

Based on Eq. (2), one can calculate the remaining service life of existing structures by measuring the carbonation depth over a certain lifetime. For newly-built structures, the diffusion coefficient k can be obtained by accelerated carbonation tests and calibrated [63] for service-life predictions. Examples can be found in Refs. [54,64,65].

3.2. Chloride-induced reinforcement corrosion

Like carbonation-induced corrosion, chloride-induced reinforcement corrosion can be also divided into two periods, with the initiation period corresponding to the penetration of chloride (Fig. 1). In this case, rebars corrode only when the chloride content of the pore solution reaches a threshold, i.e., the critical chloride content, which depends on both the types of steel and concrete and the environmental conditions [53,61]. Therefore, a general solution to the Fick's laws describing the relationship between time, depth, and concentration is needed for service-life modeling, see Eq. (3).

$$c(x,t) = c_i + c_s\left(1 - erf\frac{x}{2\sqrt{D_a t}}\right) \tag{3}$$

where, $c(x, t)$ is the chloride content at the depth x and at time t, c_i is the initial chloride content in concrete, c_s is the chloride content at the concrete surface, D_a is the apparent diffusion coefficient of chloride, and *erf* is the error function. D_a is usually time-dependent and can be written as

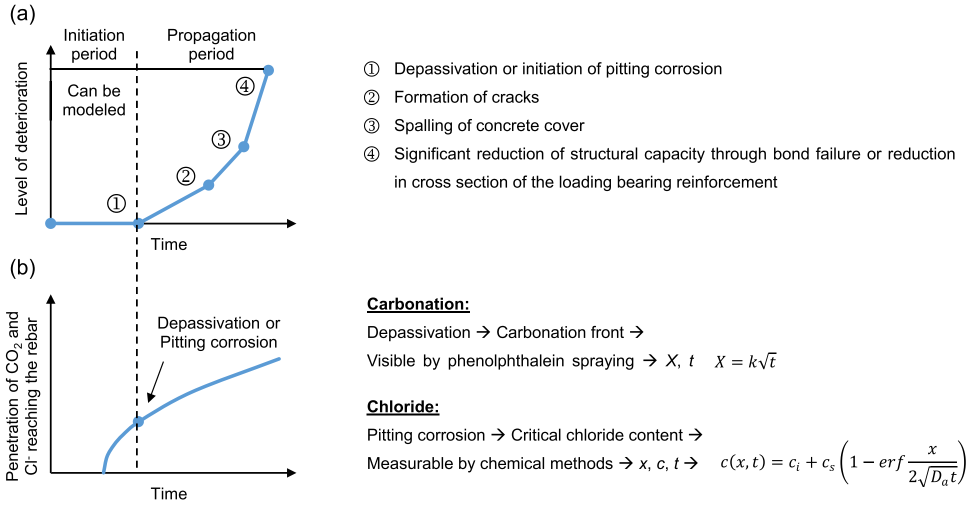

Fig. 1. Degradation models for carbonation- and chloride-induced reinforcement: (a) Two degradation periods, adapted from Refs. [52,60], and (b) Penetration of CO_2 and Cl^- reaching the rebar and service-life models associated with this process, adapted from Ref. [61].

$$D_a(t) = D_{a,0}\left(\frac{t_0}{t}\right)^{\alpha} \tag{4}$$

where, $D_{a,0}$ is the apparent diffusion coefficient measured at the reference time t_0, and α is an aging factor depending on the concrete type and environmental conditions.

For service-life prediction, c_i, c_s, and D_a can be fitted by measuring the chloride profile of existing structures with similar concrete type and exposed in similar environmental conditions. Alternatively, D_a can be calculated based on laboratory tests, e.g., from the migration coefficient obtained by the Rapid Chloride Migration method, see examples in Refs. [66–68]. Some literature (e.g., Refs. [68–70]) declares that the surface chloride content c_s and the binding capacity of chloride by cementitious materials are also time-dependent; and corrections to the prediction models are also available.

3.3. (Sulfate) chemical attack

Chemical attacks refer to the degradation of concrete induced by the interaction between cement hydration products and certain foreign ions from the environment, e.g., SO_4^{2-}, Mg^{2+}, H^+, soluble CO_2, and NH_4^+ [55,56]. These processes originate also from the penetration of ions. However, chemical reactions have a much greater impact on the ionic motion compared with the case of chloride penetration [71]. Thus, chemical attacks are usually defined as reactive transport processes. Unfortunately, these processes cannot be simply modeled by diffusion equations, and there are no internationally accepted service-life equations [55,56].

Sulfate attack is the most observed type of chemical attack. The penetration of SO_4^{2-} into concrete triggers the monosulfate-ettringite conversion [72]. Portlandite and calcium silicate hydrate (C–S–H) decompose by the leaching of Ca^{2+}, and gypsum may form in highly concentrated sulfate-bearing environments [73,74]. These reactions, including the temporal and spatial distribution of reaction products, can be modeled by numerical algorithms coupling transportation equations and chemical reactions [73,75], see Fig. 2. The formation of ettringite leads to expansive damage, and the expansion mechanism has been debated for long [76–78]. Most numerical algorithms simulate expansion damage by hypothesizing a volume increase of ettringite formation [79,80]. In parallel, the "crystal growth" theory, the most-accepted expansion theory recently, owes expansion to the formation of nano-ettringite in the mesopores of C–S–H under supersaturation [81,82]. Simulation of expansion by the latter mechanism is still scarce [75]. Ongoing efforts are undertaken to improve the reliability of service-life predictions by numerical modeling [83].

3.4. Freezing and thawing

As reviewed in Refs. [84,85], various theories have been proposed to explain the degradation mechanism in the freezing and thawing environments. Generally, it is accepted that freeze-thaw damage to concrete is attributed to the expansion induced by the water-to-ice phase transformation [86]. Thus, the ingress of water is a decisive factor for degradation, which differs from the situation of other exposure categories where water serves mainly as the media for ionic motion. In the absence of deicing salts, service life influenced by freeze-thaw damage can be predicted by modeling the water uptake by concrete (Fig. 3). The loss of strength or modulus accelerates markedly when the saturation degree of concrete reaches a threshold i.e., "critical degree of saturation"; And this is considered to be the end of a concrete's service life [87]. According to *fib* Bulletin 34 [57], this process can be modeled by Eq. (5).

$$S = S_n + e \bullet t_{eq}^{d} \tag{5}$$

where, S is the actual degree of saturation, S_n and d are materials parameters that can be measured by absorption tests, and t_{eq} is the equivalent time of wetness which is dependent on the exposure condition. A state-of-art review on the service-life prediction based on the critical degree of saturation can be found in Ref. [88].

In the presence of deicer e.g., salts, additional degradation mechanisms, i.e., surface scaling and chemical damage, to expansion damage are suggested [88–90]. Service-life models based on the critical freezing temperature is also available [57].

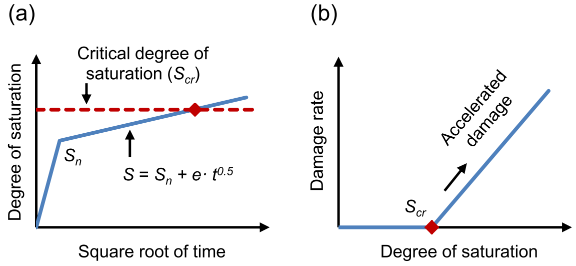

Fig. 3. Degradation models for freeze-thaw damages in the absence of deicing salts: (a) Absorption of water to reach the critical degree of saturation [88], and (b) Accelerated damage after the critical degree of saturation, adapt from Ref. [87].

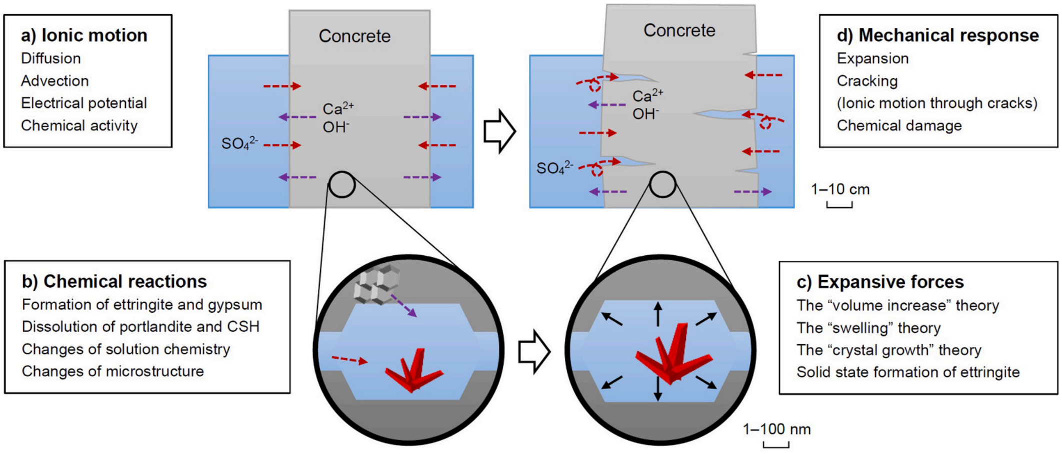

Fig. 2. Phases involved in the numerical modeling of sulfate attacks: Ionic transportation, chemical reaction, generation of expansive forces on the micro-scale, and expansive damage on the macro-scale.

3.5. Alkali-silica reaction

ASR refers to the reactions between the reactive silica in aggregates and the alkaline pore solution. Such reactions produce alkali-silica gels which can swell by adsorbing moisture, inducing the cracking of concrete. ASR requires the co-existence of 1) reactive aggregates, 2) highly-concentrated alkalis in the pore solution, 3) a source of soluble calcium to react with dissolved silica, and 4) high moisture contents in the external environment. It can be mitigated by controlling any of these factors. As reviewed in Refs. [91,92], ASR has been extensively studied in the past few decades. Various models on the physical, chemical, mechanical, or coupled aspects of the ASR process and mechanism were proposed. However, the complexity of ASR has made it difficult to validate different models; and the ASR mechanism is still open for debate. Service-life models with global consensus are still not available.

4. Coupling durability with LCA

Regulated by ISO 14040 [93], the LCA methodology consists typically of four phases: definition of goal and scope, inventory analysis, impact analysis, and interpretation. Detailed reviews of LCA applied to cement and concrete materials can be found in Refs. [31,35]. Here, existing approaches which couple the durability performance of cementitious materials with LCA are reviewed. These approaches are summarized in Table 3, and three aspects will be highlighted:

1) what can be used as durability indicators in LCA,
2) how these indicators can be incorporated into LCA, and
3) whether or not the whole structure needs to be involved.

4.1. Quantifying the durability of (reinforced) concrete: Durability indicators

In LCA, the environmental impacts are represented by environmental indicators, e.g., GHG emissions, energy use. To couple with the environmental indicators, the durability performance needs also to be quantified. Existing literature has used three types of durability indicators. Fig. 4 shows how these indicators correspond with the life-time stages of a structure. Before upscaled concrete production, the performance of concrete can be tested in laboratories, and the results can be directly used as durability indicators. During the manufacture and cast of concrete, mix proportion and the cover thickness can be adjusted for a durability design (see Section 2). These adjustments impact the raw materials demand in construction, which can be used as the second type of durability indicator. In the operation and maintenance stage, durability performance may impact the service life of structures (see also Section 3). In-use repair helps to extend the service life of a structure, which can be indicated by an increased raw materials demand. Alternatively, one can assume that all the materials and structures are demolished when the end of lifetime is reached. Such an assumption leads to the third type of indicator—service life.

4.1.1. Laboratory-based parameters

Laboratory acceleration tests are widely used to study the durability performance of cementitious materials. The results have been used as durability indicators in existing literature. In Ref. [94], chloride diffusion coefficient of concrete was considered as the indicator of chloride resistance. This parameter was coupled with the CO_2 emissions calculated by LCA to analyze the eco-efficiency of SCM-blended cement. A similar method coupling the chloride diffusion coefficient with energy consumption was adopted by Ref. [95] to study the eco-efficiency of basalt fiber reinforced concrete. The chloride ion penetration (measured in Coulombs) obtained from rapid chloride permeability tests can be a general durability indicator. This parameter was coupled with LCA to assess the eco-efficiency of rice husk ash blended concrete in Ref. [96], and discuss the selection of a functional unit by assessing the environmental impacts of concrete blended with silica fume and slag in Ref. [42].

The mechanical properties degraded by acceleration tests can be also used as durability indicators. In Ref. [97], the crushing loads of concrete samples before and after sulfuric acid immersion were measured. The results were used as the indicator of a material's durability performance in an acidic environment. In Ref. [98], the bending moment of reinforced concrete specimens before and after a four-year corrosion test was measured. It was coupled with the global warming potential (GWP) calculated from LCA to elucidate the environmental impacts of fibers on the production of green concrete containing recycled aggregates and fly ash.

Durability assessment based on laboratory tests performed in parallel with LCA without coupling was also found (e.g., Refs. [99–101]). When the "green" mixes show comparable or higher durability performance than the control group, the combined performance of the "green" mixes is assumed to be preliminarily represented by the environmental indicators. For instance, replacing Portland cement by up to 40% red ceramic waste can cut off the CO_2 intensity of cementitious materials when not significantly impacting the durability performance that is indicated by water resistance [102,103]. Such assessments, however, were not considered as a coupling approach here, as the durability indicator(s) and environmental impact indicator(s) were not combined mathematically.

4.1.2. Service life

The second approach to couple durability with LCA is to reconcile the environmental impacts with the service life of cementitious materials or structures. Usually, service life can be calculated by laboratory tests combined with the models reviewed in Section 3. The environmental impacts modeled by LCA are divided by service life to achieve the normalized/annualized impacts. This method has been used in Refs. [104–110]. Sometimes when the calculated service life exceeds a certain targeted value (for instance, a prescribed service life of 100 years for critical concrete structures specified in the ISO engineering code [111]), the targeted service life can be used as the normalizer because the calculated one may be impractical in real-world scenarios (e.g., in Refs. [104,110]).

4.1.3. Raw materials demand

As reviewed in Sections 2 and 3, the design of durable materials and structures requires adjustments on the concrete mixture and structural elements, i.e., the raw materials demand for construction is altered. Likewise, conducting in-use repair to extend the service life of structures also alters the materials consumption. Thus, the third way to incorporate durability into LCA is to model the environmental impacts associated with durability design, either on the material or the structure level, as well as maintenance actions. Compared with the other two durability indicators, i.e., laboratory-based parameters and service life, raw materials demand is more likely an "invisible" durability indicator, which means it is merged into the environmental impact indicator(s) instead of being a separated parameter or a normalizer.

Raw materials demand often applies to the carbonation or chloride-bearing environment where reinforcement corrosion governs the degradation mechanism [34,40,43,44,112–115]. Specifically, two scenarios are available (Fig. 5a). In the first scenario, durability design, either in a prescriptive manner or a performance-based one, is conducted to determine the proportioning of concrete mixes and the required cover thickness of a reinforced concrete structure (or structural element). The targeted service life is expected to be reached without maintenance. In the second scenario, a fixed cover thickness is usually given. When the service life is reached, the concrete cover is replaced by new materials, which is defined as an in-use repair action.

Although the second scenario is more widely modeled (e.g., Refs. [112–114]), the first one using a performance-based design method (e.

Table 3
A review of literature in which the durability performance of cementitious materials was coupled with LCA. RC = Reinforced concrete, FA = Fly ash, SF = Silica fume, GGBFS = Ground granulated blast furnace slag, LC^3 = Limestone calcined clay cement.

Ref.	Objective	Environmental condition	Durability indicator	Durability related actions	Modified phase		Level of assessment	
					Functional unit	Impact analysis	Material	Structure
[34]	Recycled aggregate concretes	Chloride	Quantity of raw materials	Design of cover thickness		✓		✓
[40]	Repair of reinforced concrete structures (effect of cover replacement)	Chloride	Quantity of raw materials	Maintenance (replacement of all materials)	✓		✓	
[41]	FA concrete	Carbonation Freezing and thawing	Quantity of raw materials	Maintenance (Replacement of all materials) Mix proportioning (Air entraining agent)	✓		✓	
[42]	SF and GGBFS concrete	Not defined	Rapid chloride permeability	Durability testing	✓		✓	
[43]	RC bridge edge beam and pier prepared by FA and GGBFS concrete	Freezing and thawing Chloride (from seawater and deicing salts	Quantity of raw materials	Approach 1: Mix proportioning (prescriptive durability design) Approach 2: Design of cover thickness (Performance-based design) Approach 3: Maintenance	✓			✓
[44]	RC slabs and beams prepared by FA concrete	Carbonation	Approach 1: Quantity of raw materials Approach 2: Service life	Approach 1: Design of cover thickness Approach 2: Service-life prediction		✓		✓
[94]	SF and FA concrete	Chloride	Chloride diffusion coefficient	Durability testing	✓		✓	
[95]	Basalt fiber–reinforced concrete	Chloride	Chloride diffusion coefficient	Durability testing		✓		✓
[96]	FA and rice husk ash concrete	Not defined	Rapid chloride permeability	Durability testing		✓	✓	
[97]	Steel fiber– reinforced concrete containing recycled rubber waste	Chemical (acid)	Crushing load before/after accelerated weathering	Durability testing		✓	✓	
[98]	Fiber-reinforced concrete containing recycled aggregates and fly ash	Chloride	Bending moment before/after accelerated weathering	Durability testing		✓		✓
[104]	FA concrete	Chloride	Service life	Service-life prediction	✓		✓	
[105]	FA concrete	Chloride	Service life	Service-life prediction		✓	✓	
[106]	RC bridge pier and girder prepared by FA and LC^3 concrete	Chloride	Service life	Service-life prediction		✓		✓
[107]	RC linear structural member made of GGBFS concrete	Chloride	Service life	Service-life prediction		✓		✓
[108]	Self-compacting concrete column made of GGBFS and FA concrete	Chloride	Service life	Service-life prediction		✓		✓
[109]	RC column prepared by FA and GGBFS concrete	Carbonation	Service life	Service-life prediction		✓		✓
[110]	A completely recyclable concrete	Carbonation	Service life	Service-life prediction	✓		✓	
[112]	FA concrete column	Carbonation	Quantity of raw materials	Design of cover thickness and maintenance	✓			✓
[114]	RC pier with carbon-steel and stainless-steel reinforcements	Chloride	Quantity of raw materials	Maintenance	✓			✓
[113]	FA and GGBFS concrete column	Chloride	Quantity of raw materials	Maintenance (Replacement of all materials)	✓			✓
[115]	Concrete prepared from cements of different types and strength grades	Carbonation	Quantity of raw materials	Design of cover thickness	✓		✓	
[116]	RC structures designed with concrete of different strength grades	Carbonation and chloride	Quantity of raw materials	Design of cover thickness	✓			✓
[117]	Natural zeolite blended concrete	Chemical (sulfate)	Service life	Maintenance (Replacement of all materials)	✓		✓	
[118]	Bridge girders made of UHPC and RC	Chloride	Quantity of raw materials	Structural design and maintenance	✓			✓

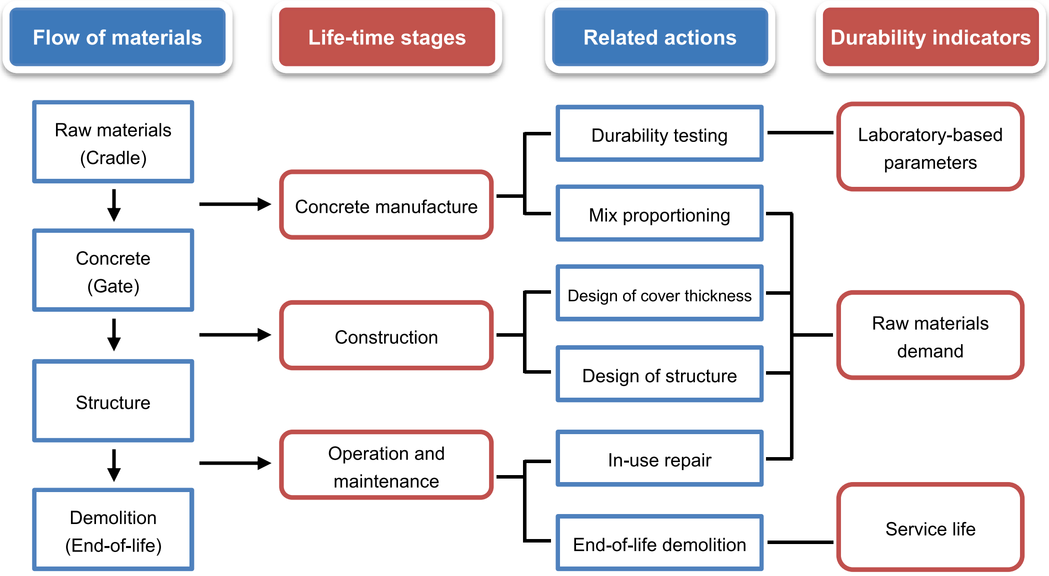

Fig. 4. Durability indicators corresponding to the life-time stages of concrete structures.

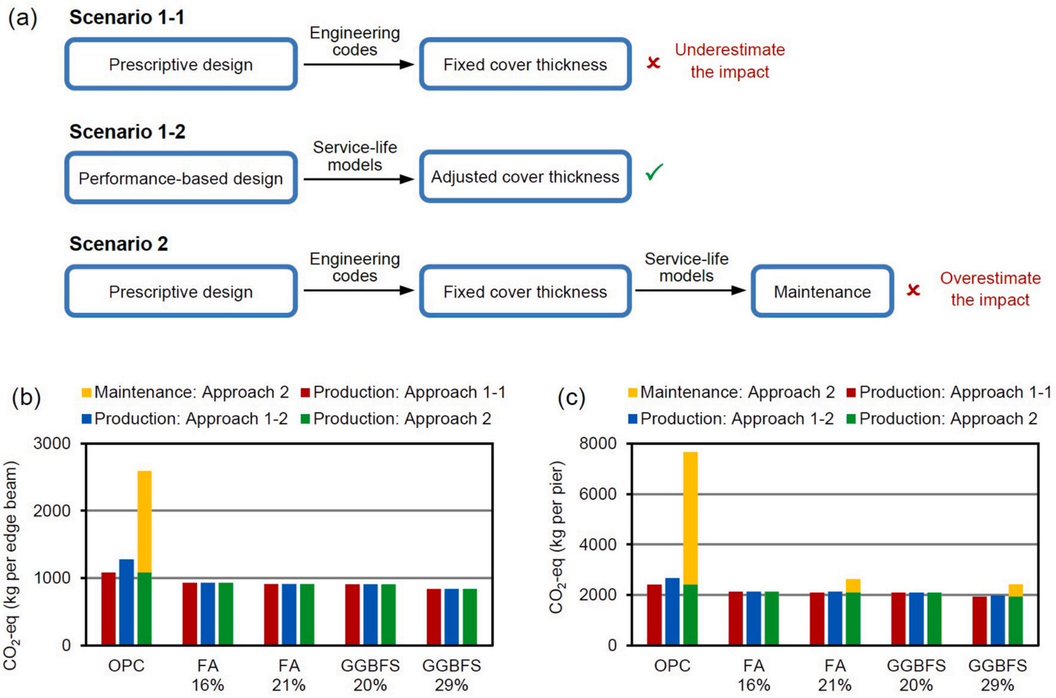

Fig. 5. Two scenarios to model the raw materials demand by durability-based LCA: (a) The methodology, (b) and (c) A comparative study provided by Al-Ayish et al. [43] on reinforced concrete bridge edge beams and piers, respectively.

g., Ref. [34]) can be more justified. This approach is supported by Ref. [40] where an increased cover thickness reduced the life-cycle environmental impacts of infrastructures by lowering the impacts associated with the maintenance phase. Al-Ayish et al. [43] provided a comparative study on these scenarios by modeling the GHG emissions of reinforced concrete structures subjected to a chloride environment (Fig. 5b and c). The prescriptive design method (Scenario 1-1) was found to mislead service life estimation, underestimating the environmental impacts. A fixed cover thickness followed by maintenance actions (Scenario 2) overestimated the impacts of a mixture having low chloride resistance (Mixture OPC without SCM addition, Fig. 5) by 2–3 times. In contrast, the performance-based design method (Scenario 1-2) reported the most justified results.

Garcez et al. [116] compared the environmental impacts of reinforcement concrete structures designed using concrete with different strength grades. Prescriptive design methods were applied and C50 concrete provides the best eco-efficiency due to the balance of raw materials demand (cover thickness) and durability (targeted service life). Marinković et al. [44] used two approaches to model the effect of service life on the environmental impacts of high volume FA (HVFA) reinforced concrete elements enduring carbonation (Fig. 6). One approach is to assign a fixed cover thickness and normalize the environmental impacts to the service life (equal to using service life as the durability indicator, see Section 4.1.2). The other is to adjust the cover

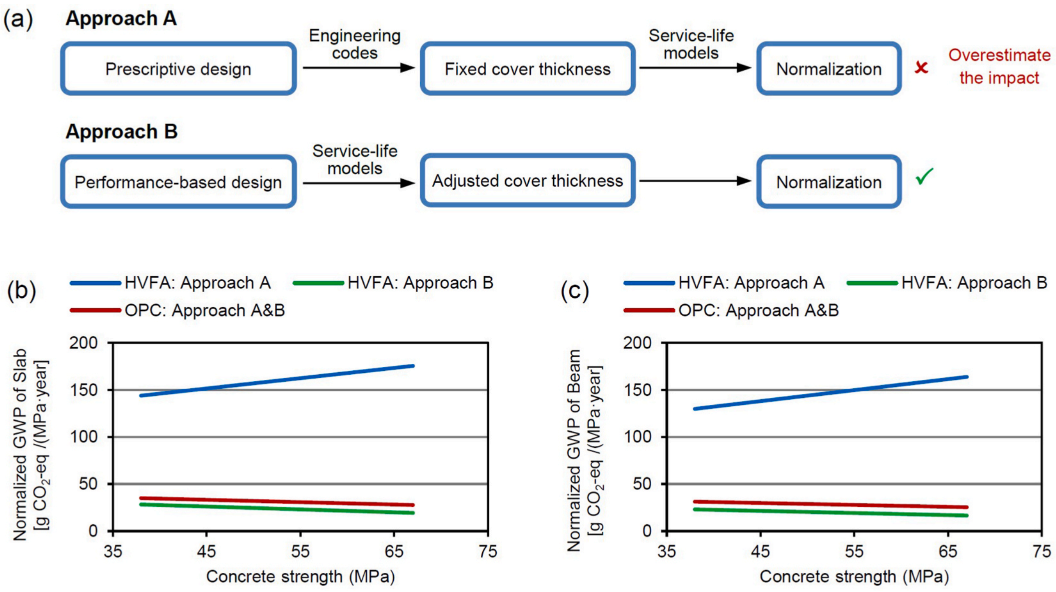

Fig. 6. Environmental impacts of high volume FA (HVFA) reinforced concrete slabs and beams modeled by different approaches: (a) Two approaches of modeling, (b) and (c) Normalized GWP of reinforced concrete slabs and beams, respectively, adapted from Marinković et al. [44]. The curves in (b) and (c) were fitted based on mix proportions obtained from the literature.

thickness based on service-life equations (similar to Scenario 1-2, Fig. 5a). The former suggests higher environmental impacts for the "green" mixes (HVFA concrete) due to lowered resistance to carbonation, but an opposite result can be found using the former approach. The results by different approaches varied by 5–10 times. They concluded that optimizing the cover thickness can help to minimize the environmental impacts on of structural elements, which is more justified than assigning a fixed cover thickness. This is also supported by Ventura et al. [115] who found that using low-permeability concrete and adjusting the cover thickness by carbonation models can save the materials consumption and drive to environmental benefits.

It should be noted that "maintenance" refers to the partial replacement of materials, e.g., the concrete cover of a reinforced concrete member. In some literature, e.g., Refs. [41,117], all the materials defined in the function unit were assumed to be replaced in a maintenance action. Such an approach leads to similar results to normalizing the environmental impacts by service life (Section 4.1.2), because all the materials are indeed demolished and reproduced by maintenance.

Modeling the quantity of raw materials can also be used to evaluate the environmental benefits brought by emerging construction materials altering the design of structures and/or cutting off the need for maintenance. For instance, Dong [118] investigated the environmental benefits of using ultra-high performance concrete in bridge construction. Compared with conventional reinforced concrete, special structural configurations without reinforcements were designed. LCA suggests a 48% reduction on CO_2 emissions due to a smaller volume of concrete required for construction and a reduced frequency of maintenance.

4.2. Coupling durability with LCA: The modified phase

A common method to incorporate the above-mentioned durability indicators into LCA is to use coupled indicators, i.e., to normalize the environmental impact indicator with the durability indicator. This method modifies the "Life cycle impact analysis" phase of LCA. For instance, the environmental impacts were normalized to the service life of concrete in Ref. [105] and to chloride diffusion coefficient in Ref. [95]. Similarly, the environmental impacts were normalized to mechanical properties in Refs. [96,99].

Another method is to modify the functional unit which is defined in the "Definition of goal and scope" phase. The selection of functional unit during LCA for cementitious materials has been extensively debated [17, 26,42,119–121]. According to ISO 14040 [93], a functional unit "defines the quantification of the identified functions (performance characteristics) of the product". It should provide a basis to quantify all inputs and outputs and allow the comparison of LCA results based on equivalent functional performance [42]. The most used functional unit is 1 m^3 of mortar or concrete (e.g., in Refs. [36,37,39,99,100]). It has been argued that such a definition cannot fulfill functional equivalence [17,42,119]. As a solution, the functional unit can be defined as 1 m^3 of cementitious materials giving 1 year of service life (e.g., in Refs. [41, 104]), or 1 m^3 of cementitious materials providing 1 unit of resistance to a certain environment (e.g., Ref. [94], used chloride diffusion coefficient as an indicator of chloride resistance, and [42,96] used rapid chloride permeability as an indicator of general durability performance) to achieve equivalent durability performance. Alternatively, the functional unit can be defined as a structural element carrying certain load. As a way of achieving functional equivalence, the modeled service life can be incorporated (e.g., Refs. [112,113]).

Although the two methods modify different phases, they may lead to similar results provided that the same durability indicator, as well as the same hypotheses in durability assessment (either modeling or testing), has been applied. Modifying the functional unit resembles moving the normalization possess forward to the "Definition of goal and scope" phase. In this respect, the selection of durability indicator and thus the way of durability assessment/quantification can play a more important role in LCA than deciding in which phase the durability indicator is incorporated.

4.3. Deciding the level of assessment: Material or structure

The review above mentioned two levels of assessments: the material level and the structure level, which are usually decided when defining the functional unit. An LCA at the material level is characterized by a functional unit related to 1 m^3 of materials, whilst one at the structure level is characterized by a functional unit based on structural elements.

An LCA at the material level takes much less efforts than that at the structure level, as structural design is not involved. However, this level of assessment is less suitable for chloride- or carbonation-induced corrosion in which reinforcement corrosion governs the degradation mechanism. In these exposure categories, the durability of a structure depends on both the performance of concrete and the design of structural elements (i.e., cover thickness). Ignoring structural design may mislead the assessment. For instance, Ref. [41] proposed a "pseudo cradle-to-gate" LCA approach. 1 m^3 of concrete with a target life span of 50 years was defined as the functional unit. Once the calculated service life was reached, the concrete was "repaired" based on a hypothesis that all materials were replaced by new ones. Apparently, such repair consumes more materials than replacing only the concrete cover provided a structural member can be defined (Fig. 7a). References [104,105] modeled the service life of cementitious materials in chloride-bearing environments, and used this parameter to normalize the environmental indicators. Similarly, this method overestimates the environmental impacts due to the lack of structural design and maintenance.

Conducting an LCA at the structure level means placing a cementitious material in a real-world working condition. More factors influencing a material's eco-efficiency can be involved to make the assessment more justified (Fig. 7b). Specifically, these factors include: 1) **The concrete cover thickness**. As discussed in the paragraph above, this factor influences the eco-efficiency of cementitious materials in the carbonation or chloride-bearing environment. 2) **The loading conditions of structural elements**. This factor was analyzed in Ref. [28] by developing equations relating the environmental impacts of members to the volume of materials required. The environmental impacts of columns are highly dependent on the compressive strength of concrete, whilst that of the beams correlates with the content of clinkers in each volume of concrete. The results were supported by case studies in Ref. [30]. 3) **The dead load of structural elements**. A structural element carries both the external load and its own weight (termed the dead load). When designing an element with low-grade concrete, a large cross-section is required, leading to more materials wasted by carrying the dead load.

LCA can also be conducted on a structure. Refs. [106,118] modeled respectively the environmental impact of a girder bridge and a reinforced concrete pier in chloride-bearing environments. The modeling covers only concrete and reinforcements, and the results are even closer to the real-world scenario than modeling simply a structural member. In other cases, non-structural elements, e.g., windows, walls, roofs, etc., can be also included when modeling the environmental impacts of a building [122–124]. The operation energy efficiency can be assessed. However, the variety of factors being involved means that this method may not be best suitable for analyzing the coupled effect of environmental and durability performance of cementitious materials.

5. Critiques and perspective

5.1. Standardizing durability-based LCA

5.1.1. Existing approaches

Existing papers used various approaches to perform durability-based LCA. To standardize the methodology, the advantages and disadvantages of these approaches are summarized in Table 4. Below, some remarks about the durability indicators are added.

Laboratory-based parameters can be obtained easily without numerical modeling for structural design and/or service life calculation. It potentially applies to all exposure categories thanks to the development of a wide variety of laboratory simulation/acceleration tests. However, such a wide variety can also lead to incomparable results. For instance, two internationally accepted methods, i.e., the steady [125] and non-steady [50,126] migration test, which generate incomparable chloride migration coefficients are available to test the chloride resistance of cementitious materials. The other problem of laboratory-based parameters is their indirect relationship with the environmental indicators. Imagine that we have a "green" mix whose CO_2 emission and chloride permeability are respectively 50% smaller and twofold higher

Table 4
Advantages and disadvantages for the methodologies reviewed in this paper.

	Advantages	Disadvantages
(1) Durability indicators		
Laboratory-based parameters	● Convenient to be performed ● Flexible, apply to all exposure categories	● Multiple methods available for each exposure category ● Indirectly correlated with environmental indicators
Service life	● Very straightforward	● May lead to inaccurate results if structural design and/or maintenance is not properly considered
Quantity of raw materials	● Closest to real-world scenarios ● Best way to model members and structures	● Too many factors available for modeling ● Standardization is needed
(2) Modified phase		
Functional unit	● Helps to achieve functional equivalence	
Impact analysis	● Easy to understand	
(3) Level of assessment		
Material	● Easy to perform	● Less suitable for chloride- or carbonation-induced corrosion
Structure	● Close to real-world scenarios	● Takes more effort

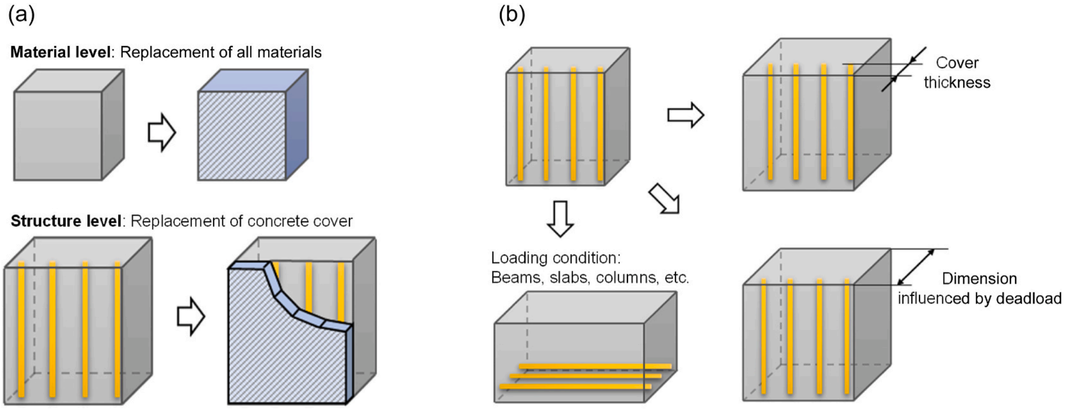

Fig. 7. Assessments at the material and structure levels: (a) Different hypotheses on maintenance, and (b) Factors that can be included in an assessment on the structure level.

than a reference mix. By simply multiplying the environmental and durability indicators (e.g., the method in Ref. [42]), we may conclude that the two mixes have similar performance in environmental and durability aspects. However, this is not always the truth because we did not quantify whether the cut-off in CO_2 emissions offsets the inferior durability performance. Thus, durability indicators based on laboratory tests are recommended only when reliable service-life models are not available [127].

Service life is very straightforward as a durability indicator. It usually applies to the carbonation and chloride-bearing environment due to the worldwide acceptance of service-life models. However, without a proper structural design, normalizing the environmental impacts directly to service life may yield inaccurate results (see the examples of [43,44] in Section 4.1.3). For some exposure categories, service-life models are not valid. One promising solution is the use of artificial intelligence in service-life prediction. For instance, Ref. [117] performed a durability-based LCA where a gene expression programming (GEP) method was used to model the service life of cementitious materials in a sulfate-bearing environment. Yet, the validity of such emerging approaches remains to be tested in the future.

Modeling the raw materials demand can well capture the effect of performance-based design method on extending the service life of structural elements. This method well reflects the working condition of cementitious materials in a structure and is suitable for the carbonation or chloride-bearing environments. The main drawback of this approach is its complexity. Many actions (e.g., mix proportioning, design of cover thickness, design of a structure, maintenance, etc.) are available for modeling, and the methodology needs standardizing.

5.1.2. *Recommendations for durability-based LCA*

In this section, a durability-based LCA framework consisting of two approaches will be provided. One approach is based on the performance-based design method and applies to the exposure categories of chloride- and carbonation-induced reinforcement corrosion. Over three quarters of existing papers model these exposure categories (Fig. 8) and divergent approaches have been selected (Fig. 9). To assure the justification of results, adjusting the cover thickness at the structure level is essential (see also Figs. 5 and 6). The following recommendations are given (see also Fig. 10):

- Define the exposure category and class, and the targeted service life; Define a structural element (e.g., beam or column) as the functional unit and make the LCA at the structure level; And define the load carried by the element when required.
- Decide the mix proportions being investigated; Refer to prescriptive specifications when required; Adjust the mix proportions, if necessary, for an improved durability performance.
- Design the thickness of concrete cover according to performance-based methods (Sections 3.1 and 3.2), ensuring that the targeted service life can be met; If the targeted service life cannot be met by a practical design, calculate the number of maintenance actions being required.

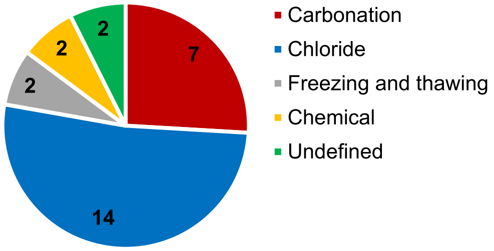

Fig. 8. Number of papers providing durability-based LCA, classified by the exposure categories.

- Add up the environmental impacts associated with all materials and processes.

When service-life models are not valid (sulfate chemical attack and ASR) or less accepted (freezing and thawing), the other approach based on the prescriptive design method is recommended. This approach also used raw materials demand as the durability indicator in order that the two approaches can be coupled when multiple exposure categories are defined (for instance, Refs. [41,43] performed durability-based LCA coupling freezing and thawing with reinforcement corrosion).

- Define the exposure category and class; Define a volume of material as the functional unit and make the LCA at the material level; And define the mechanical properties of the material if required.
- Decide the mix proportions referring to prescriptive specifications; Adjust the mix proportions, if necessary, for an improved durability performance.
- Test the validity of the material being used for the defined exposure category and class by laboratory tests; Make a conclusion of “not appropriate for the given exposure category”, if laboratory tests suggest negative results.
- Calculate the environmental impacts associated with all materials and processes.

The first approach used the performance-based models to minimize the consumption of raw materials and maximize the durability of structure elements. The results can be more justified and quantitative, as the environmental and durability performances are optimized simultaneously. In contrast, the second approach assesses the environmental impacts of possible solutions to durability issues and has a lower priority than the first one in this framework. For multiple exposure categories (involving both reinforcement corrosion and concrete damage), an assessment at the structure level (the first approach) is recommended.

5.2. *Improving the accuracy of durability-based LCA*

5.2.1. *The reliability of LCA*

To assure the accuracy of durability-based LCA, LCA needs to be conducted properly. All efforts that reduce uncertainties and avoid discrepancies can be made, e.g., defining proper system boundary, improving the reliability of data sources (e.g., by considering the regionality of materials and energy grid), and selecting proper impact indicator(s) and method of impact assessment [119,121].

One important concern of durability-based LCA lies in the definition of system boundary. As is well known, cementitious materials can capture CO_2 by carbonation. 30%–42% CO_2 emitted by the global cement industry can be reabsorbed during different modeled timespans [5,128]. As a transportation-controlled process, carbonation is highly dependent on the permeability and chemical feature of cementitious materials [129]. The amount of CO_2 being absorbed can be influenced by durability-related parameters, including mix proportions, concrete cover thickness, maintenance actions being projected, and the service life of structures. For instance, carbonation provides a 4%–25% mitigation, by type of cement, on the GWP of reinforced concrete [115]. Thus, modeling the carbonation effect by an extended system boundary covering the operation phase can improve the accuracy of LCA.

In addition to the manufacture, operation and maintenance, and demolition phases discussed in the present paper, the accuracy of durability-based LCA may also be influenced by other life-time stages. The environmental impacts brought by transportation can be modeled by LCA and may influence the selection of raw materials. Such a consideration favors the use of local materials [130,131], altering the design of concrete mixture and thus the durability performance of cementitious materials. Concrete placement and the installation of facilities during construction usually contribute small to the GHG emissions of all life-time stages. Yet, for other environmental categories, e.g.,

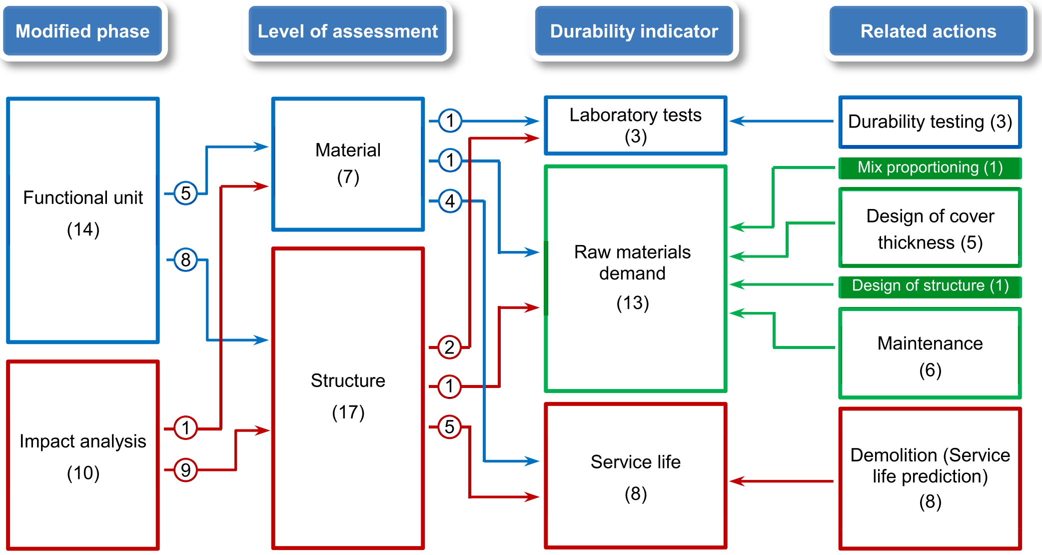

Fig. 9. Methodologies adopted by existing literature performing durability-based LCA in the exposure categories of chloride- and carbonation-induced reinforcement corrosion. 21 papers, giving 24 methods (see also Table 3) are included, with the numbers being given in the figure. It can be found that raw materials demand is the most used durability indicator, and the level of structure is more frequently selected, which coincide with our discussion in Section 5.1.1.

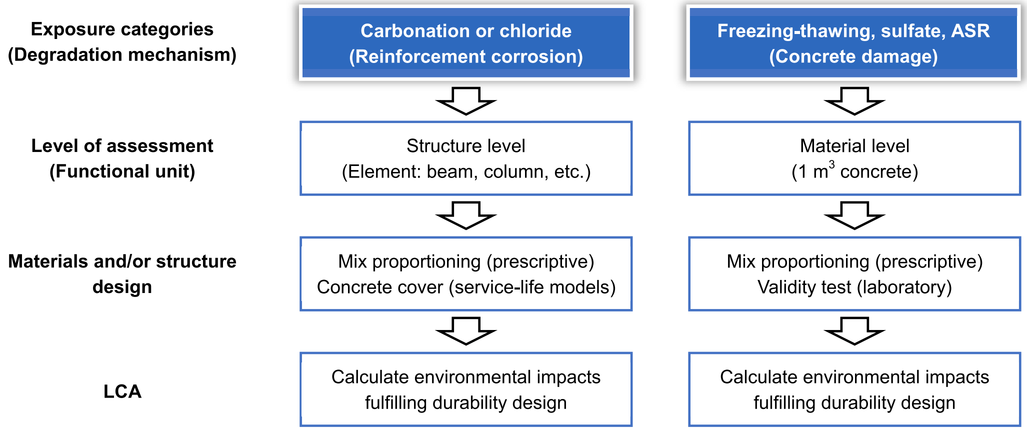

Fig. 10. Durability-based LCA framework integrating existing methodologies.

PM10, the construction phase can make a larger contribution [132]. Construction techniques and workmanship can influence the durability performance of concrete. This effect is not constantly modeled in existing studies due mainly to the unavailability of on-site data and the difficulties in quantification.

Sensitivity analysis is an important tool to study the robustness of LCA results and their sensitivity to uncertain factors, e.g., data sources and LCA models. It helps to enhance the quality of LCA. Notations on performing a proper sensitivity analysis can be found in Ref. [133].

5.2.2. *Quantification of durability*

To better quantify durability, selecting proper indicators is essential. Opon et al. [134] identified 65 indicators that had ever been used to assess the sustainability of cementitious materials, among which 11 correlate with durability (Table 5). These indicators were assigned to the social (service life) and economic (costs of production, construction, and maintenance) pillars of sustainability. Deriving from laboratory-based parameters, these indicators are not well suitable for coupling with LCA. In performance-based durability design, durability indicators, also termed durability indices (Table 5), have also been investigated [135–140]. Alexander et al. [136] provided a historical indices framework based on oxygen permeability index, chloride conductivity index, and water sorptivity index [135]. These indices/methodologies contribute to the performance-based design and service life prediction

Table 5
Durability indicators being ever used in sustainability assessment and performance-based durability design, reviewed in Refs. [134,136], respectively.

Sustainability assessment [134]	Performance-based design [136]
Resistance to chloride penetration	**Physical parameters**
Water absorption	● Permeability to liquids and/or gases
Resistance to sulfates	● Water absorption and sorptivity
Shrinkage behavior	● Porosity; pore spacing parameters
Freeze-thaw resistance	● Mechanical parameters
Carbonation	● Abrasion resistance
Abrasion resistance	**Chemical, physico-chemical, and electro-chemical parameters**
Porosity	● Calcium hydroxide content
Scaling	● Diffusivity and conductivity
Air permeability	● Resistivity
Alkali-silica reaction	● Electrical migration

associated with reinforcement corrosion. Due to the key role of the performance-based design method in durability-based LCA, these efforts can be important in the future development of the methodology. Yet, for the other degradation mechanisms, breakthroughs are still needed in both aspects for better quantifying durability.

The understand of degradation mechanisms is the key to modeling the service life of (reinforced) concrete and quantifying durability. As reviewed in Section 3, service-life models for carbonation- and chloride-induced reinforcement corrosion are better accepted. These exposure categories are more often investigated than the others in existing durability-based LCA studies. In real-world scenarios, the degradation rate and mechanism will be further influenced by the formation of cracks [141]. The transportation properties [142–144] and corrosion of reinforcements influenced by cracking has been investigated [145], and service-life models applied to cracked concrete are also available [52]. Yet, existing engineering codes used the concept of limiting crack width, specifying that cracks above a certain threshold width (usually 0.2 mm–0.4 mm) will impact directly the reliability of structures [55,56]. Sulfate attacks can be modeled by numerical methods, as reviewed in Ref. [83]. Damage models for freezing and thawing, apart from the saturation of water, are also available [146]. These methods have not been accepted by engineering codes due probably to the accuracy and practicability. Continuous work on these exposure categories will be important for durability-based LCA.

Transportation properties relate to the ease with which a fluid, ion, or molecule can move through the microstructure of cementitious materials [136]. They can potentially indicate durability independent of exposure categories [42,96]. Yet, for durability-based LCA, one key problem is how transportation properties can correlate with the environmental impact indicators, as they are usually not in the same unit or scale. Konečný et al. [127] considered laboratory-based parameters, e.g., chloride diffusion coefficient, as "pseudo" service life. They are recommended only if service-life models are not available. Gettu et al. developed two equations turning chloride diffusion coefficient and carbonation coefficient into new parameters correlating linearly with service life under given structure designs (F_{Chlor} and F_{Carb} in Table 5, and Fig. 11) [147]. Such an approach provides an important first step in revealing how laboratory-based parameters, in particular the transportation properties, can be coupled with environmental impact indicators.

5.3. Durability-based LCA vs. sustainability assessment

A similar concept of durability-based LCA is "sustainability assessment" (Table 6). Aïtcin [148] highlighted the importance of concrete strength and service life on the economic efficiency of structures in 2000, and a historical definition of sustainability index is put forward by Müller et al. who claimed that the sustainability potential of concrete and structures should be assessed in terms of environmental impact, performance, and service life [33]. Following this thinking, various indices were proposed by dividing the environmental indicators by durability indicators [147,149–151]. The other school of methods than sustainability index was developed from the multi-criteria decision support Methodology for the Relative Sustainability Assessment of Building Technologies (MARS-SC) [152] in which sustainability is assessed by quantifying, normalizing, and aggregating indicators related to the environmental, economic, and functional (mechanical property and durability) performance. Such methods were adopted by Refs. [153–155], and a combined sustainability indicator covering four aspects was developed based on these methods [127].

The propose and evolution of sustainability indices have highlighted the importance of durability in developing sustainable cementitious materials. Early studies [33,149] focused on the proportioning of cementitious materials, i.e. the production phase. For simplification, other phases were excluded, and the environmental indicators were limited to CO_2 emissions, GWP, and energy consumption. These indices provide simple ways to coupling environmental impacts with durability, but have inferior capability of quantifying environmental impacts than durability-based LCA. The methods based on MARS-SC [153–155] help to find trade-off solutions on different aspects associated with sustainability. Yet, the environmental and durability performances were quantified separately, which means an inferior capability to optimize both performances to durability-based LCA.

5.4. More concerns about future work

New cements, also termed alternative binders, are considered as important decarbonizing approaches for the cement and concrete industry. Their decarbonization potentials vary by raw materials demand, energy consumption for production, process-related emissions, and capability of CO_2 absorption [2]. The durability performance of alternative cementitious materials, e.g., resistance against CO_2 transportation, chemical/microstructural response to carbonation, and depassivation mechanism [156–158], can deviate largely from Portland cement materials. For instance, reactive magnesia cement offers 73% CO_2 mitigation potential than Portland cement due to the low calcination temperature of MgO and its capability of CO_2 absorption [159]. This cement is highly resistant to sulfate attack, freezing and thawing, and chloride penetration [160–162]. However, it is not able to depassivate reinforcements due to the low alkalinity and thus may not be suitable for reinforced structures [163]. For such new cements, existing methodologies for durability design and service-life prediction need to be tested. Methodologies coupling the environmental and durability assessments will also be required for future work.

Emerging techniques, e.g., protective coating, cathodic protection, self-healing techniques, can be possible solutions to enhancing the durability of reinforced concrete. These techniques alter the traditional way of material/structure design, structure operation (in terms of energy consumption), and maintenance actions. LCA on these techniques are available [164–167], but the difficulties in a precise prediction of service life due to unconventional operation mechanisms may bring uncertainties to LCA. More work will be required on the mechanism,

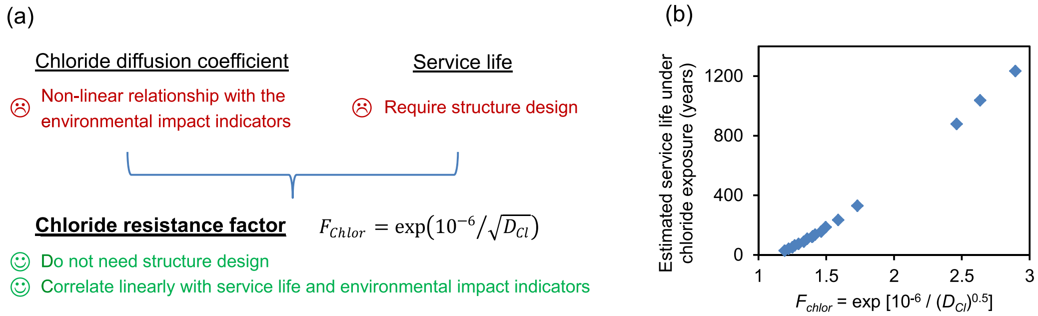

Fig. 11. Chloride resistance factor (a), and its relationship with service life in the chloride environment (b), adapted from Ref. [147].

Table 6
Historical sustainability indices and methodologies for sustainability assessment.

Year	Author	Ref.	Methodology of sustainability assessment	Equation	Durability indicator
2000	Aïtcin	[148]	**Economic efficiency** of concrete: the cost of 1 MPa or 1 year of life cycle of a structure		Service life
2006	Mateus and Bragança	[152]	**MARS-SC:** three groups of sustainability categories, i.e., environmental, functional and economic	$ND_A = \sum_{i=1}^{n} w_i \bullet \overline{P_i}$ where, $\overline{P_i} = \frac{P_i - P_{*i}}{P_i^* - P_{*i}} \forall i$	Not specified, laboratory-based parameters related to carbonation resistance or chloride resistance in [153–155]
2010	Damineli et al.	[149]	**Binder intensity**: the total amount of binder necessary to deliver one unit of performance **CO_2 intensity**: the amount of CO_2 emitted to deliver one unit of performance	$b_i = \frac{b}{p}$ $c_i = \frac{c}{p}$	Not specified
2014	Müller et al.	[33]	**Sustainability potential**: Proportioning of concrete mixes with minimum environmental impacts and maximum lifetime performance	$\Omega = \frac{f_{ck} t_{SL}}{GWP}$	Service life
2018	Gettu et al.	[147]	**Energy intensity**: the energy consumed in the production of unit volume of concrete divided by the compressive strength at 365 days **A-index**: the total carbon emissions attributed to a unit volume of concrete divided by a material durability parameter	$Ai = \frac{CO_2 (per\, m^3)}{F}$ where, $F_{Chlor} = \exp(10^{-6} / \sqrt{D_{Cl}})$ $F_{Carb} = \left(\frac{5}{k_{CO2,Nat}}\right)^2$	Modified parameters related to chloride diffusion coefficient and carbonation coefficient
2020	Konečný et al.	[127]	**Sustainability indicator**: A combination of performance, durability, eco-cost, and mixture costs	$k_{SB} = \frac{w_R \frac{R}{R_{ref}} \bullet w_L \frac{L}{L_{ref}}}{w_E \frac{E}{E_{ref}} \bullet w_C \frac{C}{C_{ref}}}$	Service life or other durability indicators

efficiency, and real-world performance to better assess their eco-efficiency [168,169]. For those techniques requiring energy inputs during operation (e.g., cathodic protection), their eco-efficiency needs to be analyzed critically considering the diversity and future development of energy grids.

Advancing new engineering codes and methodological frameworks are essential to implement our current understanding of sustainable concrete. The durability-based LCA framework presented here is established on existing method of durability design (i.e., the prescriptive and performance-based design method). By upgrading current engineering codes, this framework can be a good choice of next-generation codes coupling durability and environmental design. In the upcoming *Fib* model code 2020, sustainability will be taken as a fundamental requirement for durability design [170], and the new methodology is also anticipated. Besides, an increasing number of studies are devoted to developing multi-objective design approaches by computational modeling [171,172]. Advancement in this area requires both well-developed algorithms and a deepened understanding of durability and LCA.

6. Conclusions

Durability is an important factor influencing the eco-efficiency of cementitious materials. This effect can be investigated by performing durability-based LCA. Existing literature provided divergent approaches which used different durability indicators (laboratory-based parameters, service life, and raw materials demand) and conducted assessments at different levels (the material level and the structure level). At most tenfold variations may be observed through different approaches. To facilitate a standardized methodology, a durability-based LCA framework integrating two approaches is proposed here. These approaches are based on the prescriptive and performance-based durability design methods, and apply to exposure categories associated with concrete damage (freezing and thawing, sulfate attack, ASR) and reinforcement corrosion (carbonation and chloride), respectively.

The development and standardization of durability-based LCA require efforts on both LCA methodology and durability. One key work lies in exploring degradation mechanisms and developing service-life models, as performance-based design methods are the key to optimizing the environmental impacts (i.e., raw materials demand) and durability performance of structural elements. The two approaches in the proposed durability-based LCA framework couple LCA with existing methods of concrete design. Therefore, the framework can be integrated into engineering codes, making a next-generation design method highlighting sustainability. This review provides potential areas to future research including developing new durability indicators, investigating the eco-efficiency of new cements and techniques, and advancing new methodological frameworks.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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