Next Sustainability 3 (2024) 100025

Contents lists available at ScienceDirect

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Review article

Impact of concrete structures durability on its sustainability and climate resiliency

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ARTICLE INFO

Keywords:
Concrete
Concrete properties
Durability
Sustainability
Climate resiliency

ABSTRACT

Durability property is a critical performance indicator of concrete in different environments and locations. However, durability also plays a key role in the sustainability and climate resiliency of concrete structures which is mostly ignored in the context of ways to improve the sustainability of concrete materials and structures. Hence, this paper aims to bring focus to this area by presenting an overview of the critical role of concrete properties especially durability on the sustainability and climate resiliency of concrete structures. This paper first presents a general overview of concrete materials followed by the connection of concrete to sustainability and climate resiliency. Discussions from this paper indicate that to improve concrete sustainability, there is a need to use materials with lower environmental impacts upfront in addition to producing concrete with improved durability to ensure long-term performance. In other words, merely reducing the upfront embodied carbon of materials is not sufficient to achieve sustainable concrete if the impact of such alternative low-carbon materials used to replace the traditional materials in concrete is not considered. On the other hand, the climate resiliency of concrete structures is mostly dependent on improved durability which would sustain their adaptation over time to the impacts of the changing climate conditions. Overall, to achieve sustainability and climate resilience of concrete structures; lower environmental impact, higher durability performance and resilience to applicable climatic conditions must be achieved.

Introduction

Concrete being the most used construction material in the world can be associated with its outstanding performance coupled with its lower cost and availability of raw materials locally in various parts of the world. Concrete has been used extensively to build various infrastructures ranging from transportation systems, health, residential and commercial buildings, water systems, etc. However, the high production and use of concrete have been found to yield negative environmental impacts on the environment due to its contribution to greenhouse gas (GHG) emissions and consumption of natural resources [1,2].

In contrast to other construction materials, such as steel and glass; concrete has a lower unit embodied carbon as depicted in Fig. 1 which shows the carbon emissions per kilogram of each material. However, the production and use of concrete in large quantities have resulted in the concrete industry being a major contributor to the world's human-induced GHG emissions. A critical part of concrete responsible for the high GHG emission is the production of portland cement (PC) which is the primary binder in concrete and other cementitious materials. Out of all cementitious materials (i.e. concrete, mortar, grout, etc.), concrete consumes PC the most with an estimated amount of 70% while the other 30% is used for other cementitious materials such as mortar, grout, etc.

More than 4 billion tons of PC are now produced annually worldwide [4] with an annual increase of up to 23% expected by 2050 [5] due to rapid urbanization and an increase in population. For comparison, the amount of PC and concrete produced and other common materials by humans is presented in Table 1. The projected amount of PC to be produced by various regions is presented in Fig. 2. It can be noted from Table 1 that the amount of concrete produced is significantly higher and more than the production of all other materials stated. For example, the amount of concrete produced is approximately 15 times and 75 times

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Abbreviations: CO_2, Carbon dioxide; FA, Fly ash; GHGs, Greenhouse gasses; MK, Metakaolin; NPC, Normal performance concrete; PC, Portland cement; SF, Silica fume; SL, Slag; SCMs, Supplementary cementitious materials; UHPC, Ultra-high performance concrete.

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https://doi.org/10.1016/j.nxsust.2024.100025
Received 8 December 2023; Received in revised form 23 January 2024; Accepted 24 January 2024

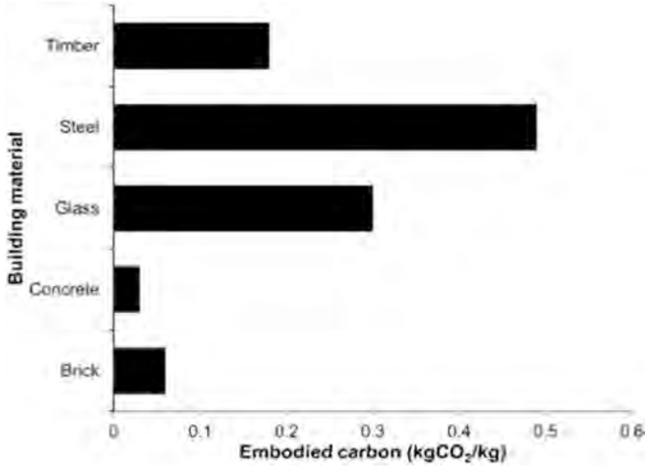

Fig. 1. Embodied carbon of building materials [3].

Table 1
Estimated amount of materials produced annually*.

Material	Amount
Portland cement	4.4 billion tons
Concrete	30 billion tons
Plastic	367 million tons
Steel	1.9 billion tons
Sugar	181 million tons
Gold	3200 tons
Silver	24,000 tons
Salt	290 million tons
Wheat	750 million tons

* data obtained from different sources

that of steel and plastic, respectively. Hence, concrete has been deemed the most produced man-made material and the most consumed material after water.

With the high production and use of concrete comes a correspondingly high production of PC and a consequential increase in GHG emissions. The high use of PC and concrete for various construction applications has been estimated to contribute to about 10% of the anthropogenic carbon dioxide emissions (CO_2) of 2019 alone [7]. In addition, for the production of one ton of PC, about 1.5 tons of raw materials are needed which also requires about 3500 MJ to 7000 MJ of energy for processing. Hence, the high production of PC and the corresponding production of concrete not only result in high emissions but also result in the over-exploitation of natural resources [3].

Life cycle assessment of concrete structures has indicated that the production of PC alone is responsible for about 77% of the cumulative CO_2 emissions associated with the production, use and disposal of concrete as shown in Fig. 3. However, it can be observed from Fig. 3 that no emission is linked to the use which is not necessarily correct. The use of concrete structures would result in some maintenance, rehabilitation or replacement which would have associated emissions. The emissions from the use would also be related to the durability performance and climate resilience of the concrete structure as that would determine how often such concrete structure has to be repaired, rehabilitated or replaced which would result in more consumption of raw materials and a consequential increase in GHGs. Hence, it is critical to consider the emissions associated with the usage of concrete (i.e. operational emissions) in order to have a more accurate life cycle assessment. However, the emission from PC production would still be predominant unless alternative low-carbon materials are used as substitutes.

The International Energy Agency (IEA) report [8] indicated there is a need for an annual 3% decline in the carbon emission from PC production up to 2030 in order to counteract the 1.5% increase in the carbon emissions that occurred between 2015 to 2021 and achieve a net-zero emission by 2050. Several initiatives have been employed by the construction industry which have resulted in about a 20% reduction in CO_2 emission, a 17% reduction in the use of fossil fuel and a 19% increase in energy efficiency improvement per ton of PC produced since 1990 [9]. Governments such as the Government of Canada are also working actively to decarbonize the construction industry by having net-zero carbon concrete by 2050 [10]. Cementitious materials such as concrete also sequester CO_2 during their service life which is a slow process and it has been estimated that about 4.5 Gt of CO_2 have been sequestered in cementitious materials between 1930 to 2013 [11]. However, there still exists a significant contribution of the production of

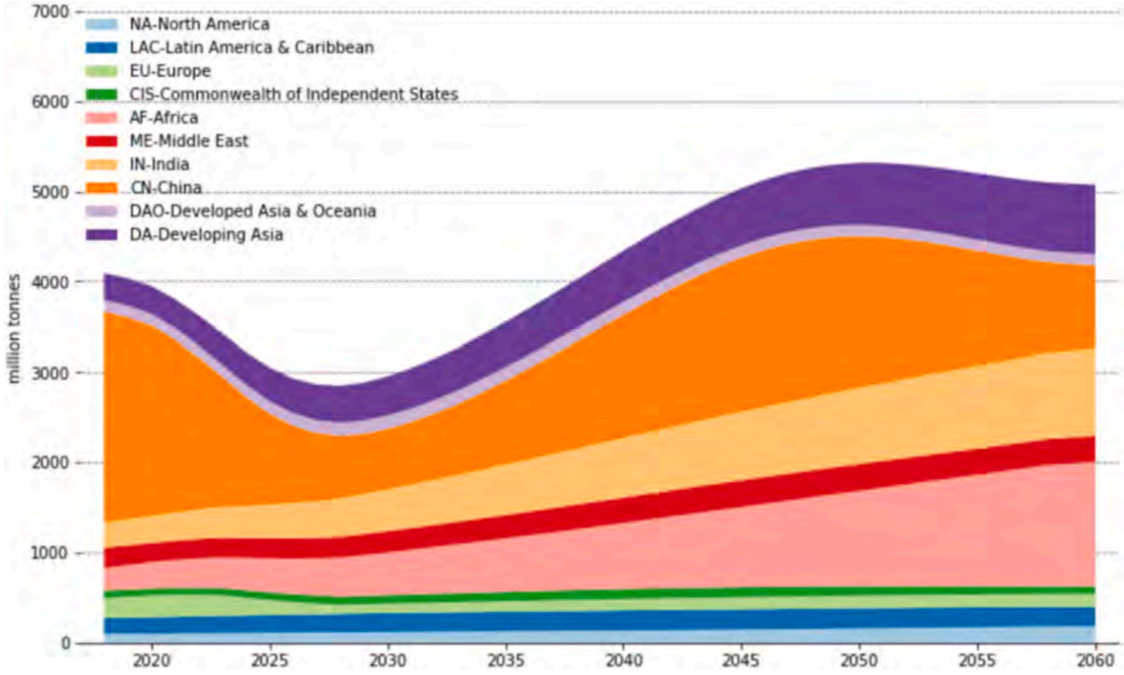

Fig. 2. Projected PC production [6].

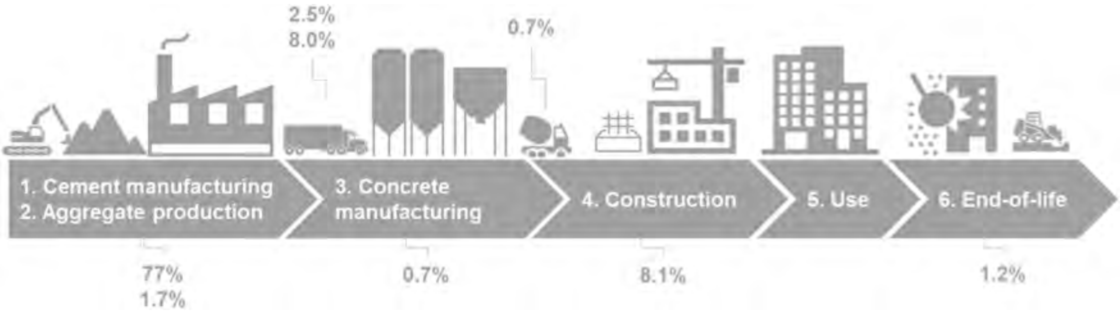

Fig. 3. CO_2 emissions from life cycle assessment of concrete structures [6].

PC and concrete to GHGs due to the high production.

The carbon emission of concrete structures (i.e. embodied carbon) is mostly used as an indication of its sustainability as it covers the CO_2 emission associated with various stages and recycling of concrete as shown in Fig. 4. Several studies have calculated the embodied carbon of various concrete mixtures and structures as an indication of sustainability [12–15]. However, an overlooked part of concrete sustainability is the relationship between this embodied carbon of concrete and its performance (i.e. durability and mechanical properties). Whereas, an effective approach to enhance the overall sustainability of concrete structures is through the design of concrete for better durability and climate resiliency rather than just the embodied carbon of the materials used in the production of concrete. Such effective design for durability and climate resiliency would reduce or eliminate the need for the occasional use of additional materials for the repair or replacement of concrete structures.

A more durable concrete is expected to have a longer service life resulting in the elimination of the use of more materials for repair or replacement. In fact, while trying to enhance the durability of concrete; the most commonly used approach would involve the use of lower embodied materials (i.e. supplementary cementitious materials (SCMs) which would result in an overall reduction of the embodied carbon of concrete. Nonetheless, some studies have created a form of index to compare various properties of concrete with its sustainability. For example, Rathnarajan and Dhanya [17] correlated the long-term strength, energy demand and carbon emissions in the form of an index. A similar correlation was also done by Henry et al. [18] where the durability and environmental impact of recycled aggregate concrete was also evaluated.

While considering the sustainability of concrete, it is also critical to consider the climate resiliency of concrete infrastructures as this contributes to the overall sustainability of concrete. Climate resiliency of concrete structures is the ability of the resulting structure to recover from or withstand external stressors or damage. Concrete structures designed to withstand specific detrimental occurrences of climate change would result in no or minimal rehabilitation thereby eliminating much emissions associated with the use of raw materials for new construction. Hence, the durability of concrete also plays a critical role in sustaining the climate resiliency of concrete structures. However, there is a limited connection between the durability of concrete and its resulting sustainability and climate resilience.

Hence, the primary objective of this paper is to gear a discussion toward the critical role of concrete properties especially durability on the sustainability and climate resiliency of concrete structures. In this paper, discussions on the properties of concrete were made and correlated with the corresponding sustainability and climate resiliency of concrete structures. Concrete properties in terms of mechanical and durability were first discussed followed by the discussion on the factors that affect concrete sustainability and climate resiliency. It is anticipated that the discussion in this paper will bring more focus on the critical role of durability in the sustainability of concrete and its climate resiliency. It is also hoped that the design for concrete sustainability would involve

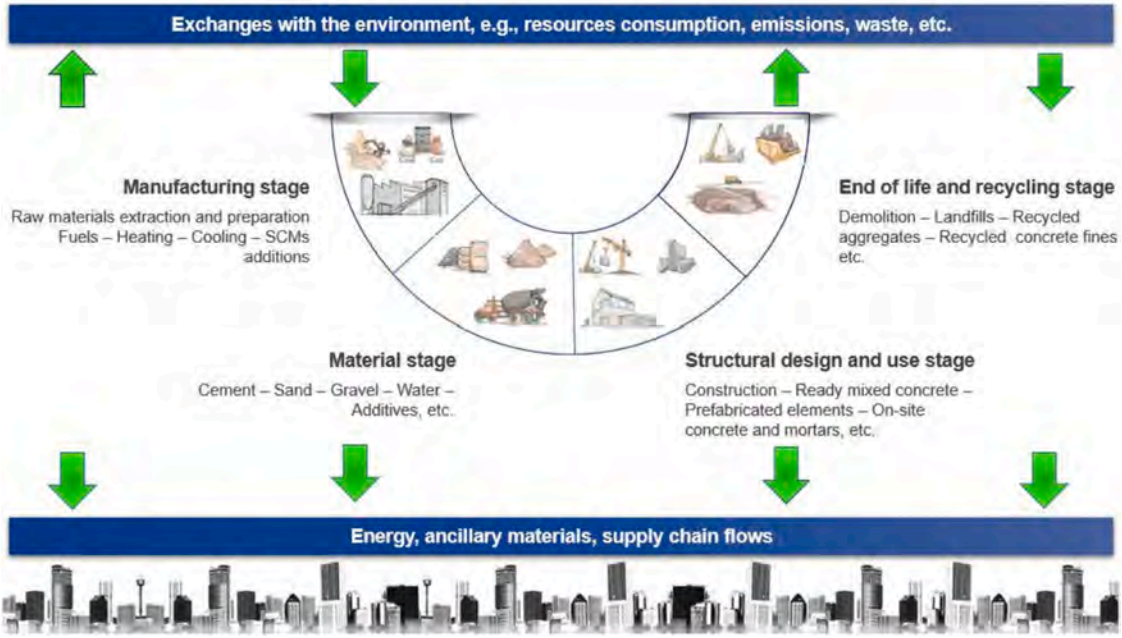

Fig. 4. Factors considered in embodied carbon of concrete [16].

designing for durability and longer service life in order to reduce the life-cycle carbon rather than just the embodied carbon.

Concrete properties

As with any other material, concrete has various properties ranging from physical properties to fresh and hardened properties. These properties are influenced by the composition of the concrete, the production process and the chemical/physical environment to which they are subjected. In terms of performance in the hardened state; concrete properties can be generally classified into mechanical and durability properties. The mechanical properties of concrete cover the ability of the concrete composite to withstand various physical forces. Some of the mechanical properties of concrete are compressive strength, flexural strength, shear strength, etc.

The compressive strength of concrete is primarily dependent on the binder content as shown in Fig. 5. However, other factors such as water content, aggregate type and content, admixtures, reinforcements, etc. also influence the compressive strength [19]. Other mechanical properties such as tensile strength and flexural strength are also primarily dependent on the type and amount of reinforcement in addition to binder content and other factors. However, compressive strength is used as the basis for concrete design.

On the other hand, the durability properties of concrete give an indication of how the concrete can withstand various deleterious forces in the environment to which it is located or exposed. The main factors that control the durability of concrete are absorption, permeability and diffusion. Common durability properties of concrete are water absorption, chloride ion penetration, shrinkage, etc. From the definition of these two broad categories of concrete properties; it is evident that concrete with higher mechanical properties does not necessarily mean durable concrete. Studies have also shown that there is no direct correlation between the strength and durability of concrete [21]. Due to the use of concrete for the construction of various critical and core infrastructures, it is essential that concrete is designed and constructed for high durability in order to achieve longer service life for the resulting structures. Thus, the durability property requirement of concrete should be based on both the application and environment to which the concrete structure would be subjected while the mechanical property requirement is mostly dependent on the application of the concrete. Hence, to ensure long-term performance concrete, the concrete must meet the requirements for strength, durability and serviceability for the application as depicted in Fig. 6**.** The serviceability of concrete refers to the ability of the concrete to perform its intended function without excessive cracking or deformation. This includes factors such as cracking, deflection, and durability. The serviceability of concrete is important because it affects the structural integrity and overall performance of the concrete structure. Fig. 7 gives a depiction of the serviceability of concrete showing the performance requirement of concrete is met over its intended service life.

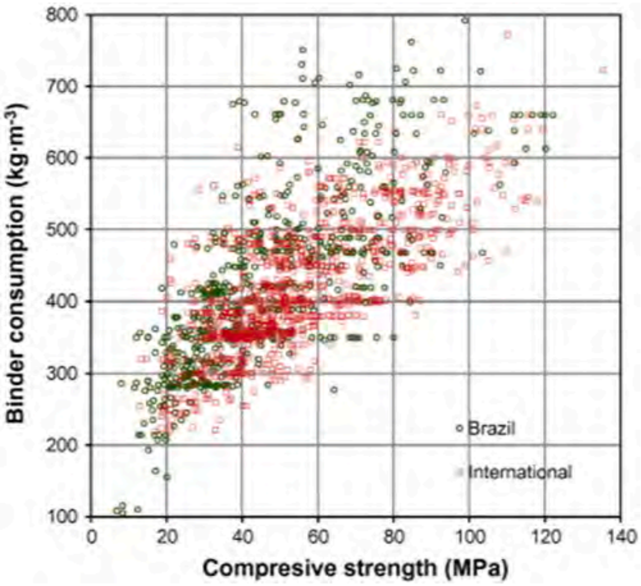

Fig. 5. Influence of binder content on the 28 days compressive strength. Reused with permission from Damineli et al. [20].

Enhanced concrete durability can be achieved through quality control of materials, mixture design optimization, use of SCMs, use of admixtures, good production procedures, etc. With concrete being a relatively porous material; its durability is dependent on the ease with which various materials can penetrate and alter different concrete products as shown in Fig. 8. Due to the significant impact of concrete porosity on major durability problems, permeability or porosity of concrete can be used as a good indication of the whole durability of concrete. The influence of various parameters on the durability of concrete is shown in Fig. 9. However, it is worth mentioning, that other factors such as cracking, volumetric changes, impact, etc. also play a significant role in the durability of concrete.

Sustainability and climate resiliency of concrete

Concrete sustainability

Concrete sustainability is mostly associated with the embodied carbon of its constituent materials such as the binder, aggregate, admixtures, etc. However, the sustainability of concrete encompasses the materials, the production process and its performance including its corresponding impact on the environment, society and economics. Thus, considering only the concrete materials and process involved in its production is not enough to assess concrete sustainability without considering the durability and performance of the concrete as it is expected to have a certain service life ranging from 50 years to 100 years.

As shown in Fig. 10, it is evident that designing concrete for durability, strength and serviceability results in long-term performance. The critical role of durability on the service life of concrete structures and the corresponding sustainability can also be depicted as shown in Fig. 10. Fig. 10 shows a schematic relationship between the durability of concrete and service life. Structure A has an enhanced (i.e. higher) durability compared to that of structure B. Hence, the longer service life of structure A eliminated the need to use raw materials and energy for unplanned rehabilitation. Thus, concrete structures with long-term performance would require lower maintenance and eradicate the need to replace within a short period of time thereby eliminating the need for additional materials and resources for the new construction. Hence,

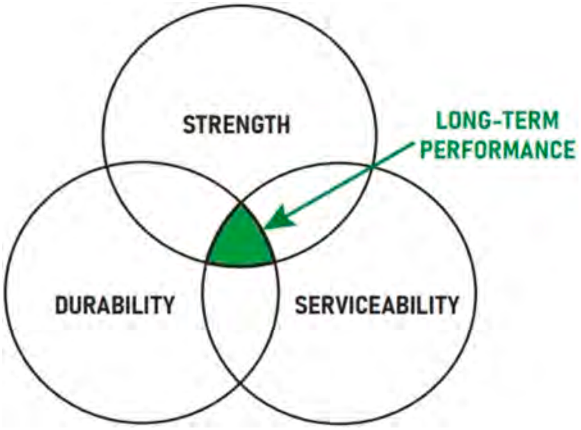

Fig. 6. Achieving long-term performance for concrete.

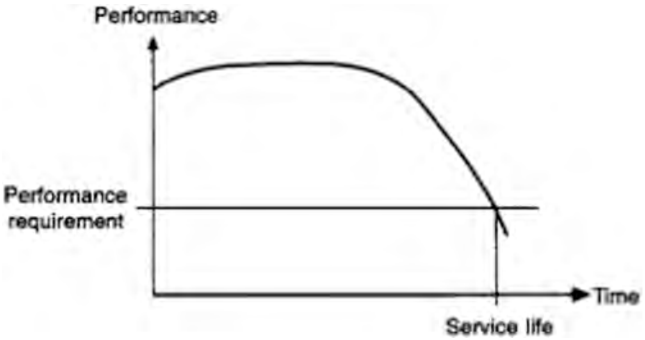

Fig. 7. Serviceability of concrete [22].

long-term performance concrete contributes to the sustainability of the concrete.

Sustainability as a whole is an intersection between environmental performance, social performance and economic performance. However, most focus on concrete sustainability is placed on environmental impact mostly in terms of embodied carbon while the economic aspect is rarely considered and social performance is totally ignored. Thus, to effectively determine the sustainability of concrete structures, all these three arms need to be considered and should cover all the processes involved in the production of the materials, construction process, and maintenance. Based on these components of concrete performance, the overall sustainability of concrete structures can be simplified using Eq. 1. It is worth mentioning that the long-term performance (P_l) encompasses strength, durability and serviceability as depicted in Fig. 6. The environmental impacts (I_e) to be considered for the equation should not be restricted to only the embodied carbon of the materials and processes but also various environmental impacts deduced from a comprehensive life cycle assessment.

$$Concrete \quad Sustainability \quad (C_s) = \frac{Long-term \quad Performance(P_l)}{Environmental \quad Impacts(I_e)} \tag{1}$$

Thus, using only the environmental impact is not accurate in determining the overall sustainability of concrete. In some cases, higher environmental impact does not necessarily mean lower sustainability if the performance of the concrete is not considered. For example, the study by Müller et al. [25] showed that ultra-high performance concrete (UHPC) has higher environmental impacts compared to normal performance concrete (NPC) as shown in Fig. 11. However, when the corresponding performance of the UHPC in terms of the water absorption is compared with the resulting environmental impacts, it was found that UHPC has lower environmental impacts compared to NPC as shown in Fig. 12. The lower environmental impact of UHPC compared to NPC when the durability is considered is due to the lower water absorption of UHPC which indicates more resistance to the ingression of deleterious ions and fluids resulting in longer service life. Hence, it is critical for the sustainability of concrete not to be dependent on solely the environmental impacts but must be correlated with the performance.

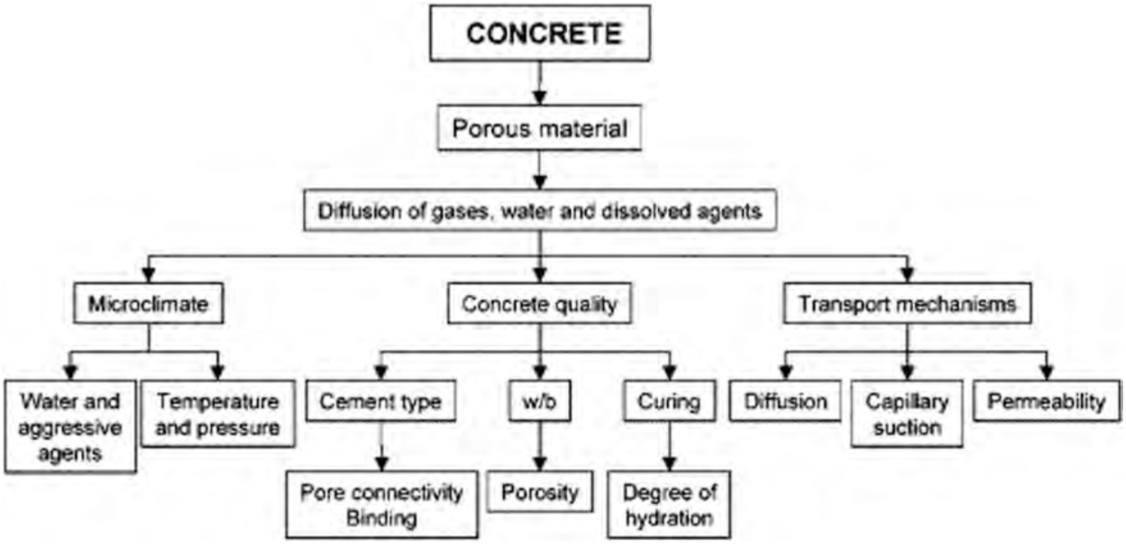

Fig. 8. Dependency of concrete durability on porosity (reproduced with permission [23]).

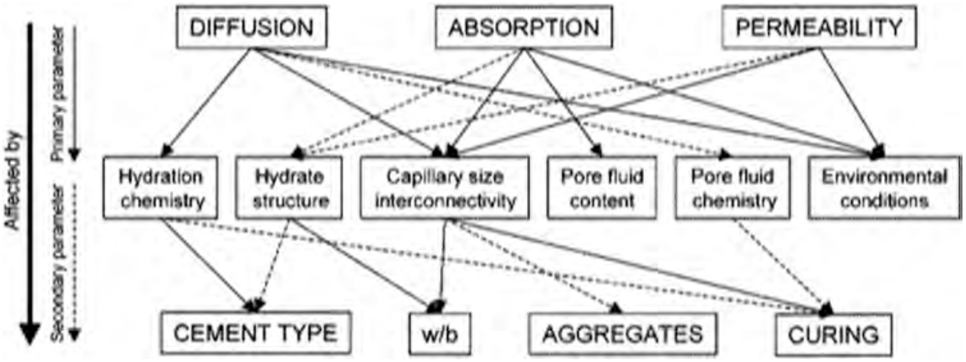

Fig. 9. Parameters influencing concrete durability (reproduced with permission [23]).

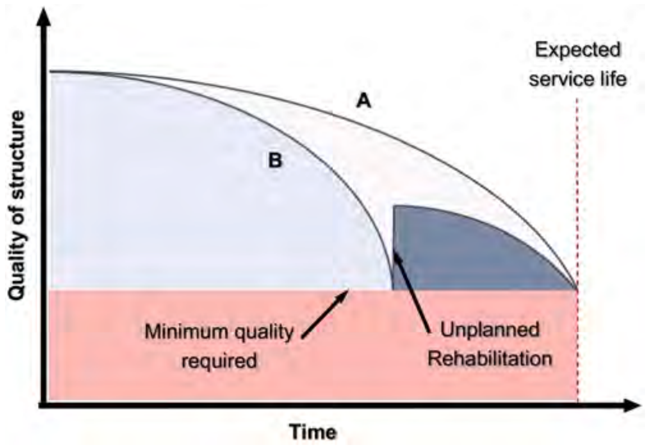

Fig. 10. Service life of concrete structures with different durability (reproduced with permission [24]).

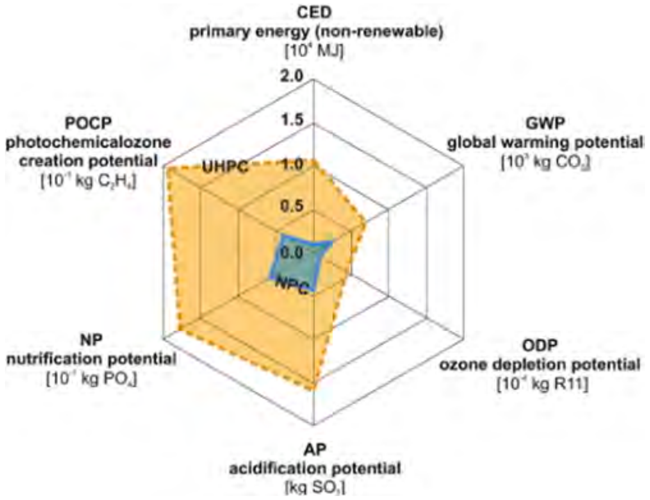

Fig. 11. Environmental impacts of UHPC and HPC (reproduced with permission[25]).

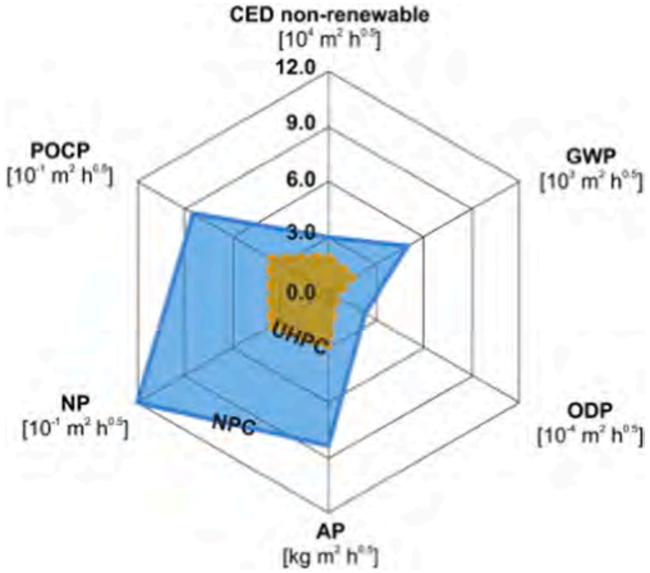

Fig. 12. Environmental impacts of UHPC and HPC relative to durability (reproduced with permission[25]).

Climate resiliency of concrete

The changing climate poses a threat to the resiliency of concrete structures as environmental conditions for which concrete structures are typically designed are no longer the current environmental conditions nor a representation of future conditions. The increasing global warming has resulted in climate changes resulting in many natural detrimental occurrences getting rampant in recent times. Some of these detrimental occurrences range from extreme cold and heat to earthquakes, hurricanes, fires and volcanic events. A recent occurrence with a highly damaging impact on various infrastructures including concrete structures is Hurricane Ian which transformed into a category 4 hurricane and hit Florida in September of 2022 [26], with damage exceeding 50 billion US dollars. Table 2 shows the possible impacts of climate change occurrence on concrete structures and Fig. 13 shows how the impacts from climate change consequentially affect buildings and the corresponding occupants.

According to the Intergovernmental Panel on Climate Change [28], 'resilience' is the "ability of a system and its counterparts to anticipate, absorb, accommodate or recover from the effects of a hazardous event in a timely and efficient manner". Thus, the ability of concrete structures to adapt and maintain their serviceability in the changing climate is critical as it affects their overall performance and resilience. Hence, while focusing on the sustainability of concrete; it is critical to also incorporate the climate resiliency of the concrete.

It is worth emphasizing that there is a clear distinction between the sustainability of concrete and the climate resiliency of concrete. A concrete structure sustainable in terms of the materials and processes involved in the construction might not necessarily have good climate resiliency. Thus, in addition to improving the sustainability of concrete structures, initiatives should be put into place to improve concrete resiliency as this contributes to the overall sustainability of concrete. For example, a concrete pavement (i.e. rigid pavement) designed for high climate resiliency would survive various impacts of climate changes resulting in the reduction or elimination of the need to rehabilitate or replace. On the other hand, a sustainable concrete structure with performance alteration during a major climate change impact such as a hurricane might need replacement resulting in the use of raw materials and additional processes thereby counteracting its sustainability. Nevertheless, it should be noted that durability contributes significantly

Table 2
Impact of climate change on concrete structures.

Climate change Occurrence	Impact on concrete structures
Wildfires	1. Spalling due to high volumetric changes 2. Reduction of load capacity due to deterioration of hydration products
Flooding	1. Corrosion due to more ingress of salt water 2. Loss of stability such as road sub-base and embankments 3. Accelerated deterioration due to abrasive forces 4. Rupture of water concrete infrastructures due to increased capacity
Hurricane	1. Flooding of concrete elements and structures e.g. dams
High sea level	1. Increased corrosion due to contact of structures with salty water 2. Submergence/sinking and collapse of structures due to loss of base
Storms/ high winds	1. The collapse of vertical infrastructures 2. Damage of structure due to impact from lifted objects
Extreme cold	1. Permafrost degradation 2. Higher freeze-thaw cycles resulting in faster degradation 3. Corrosion due to the use of high amounts of salts 4. Rupture of water storage tanks due to an increase in the volume of water
Extreme heat	1. Expansion and thermal cracking 2. Reduction in service life

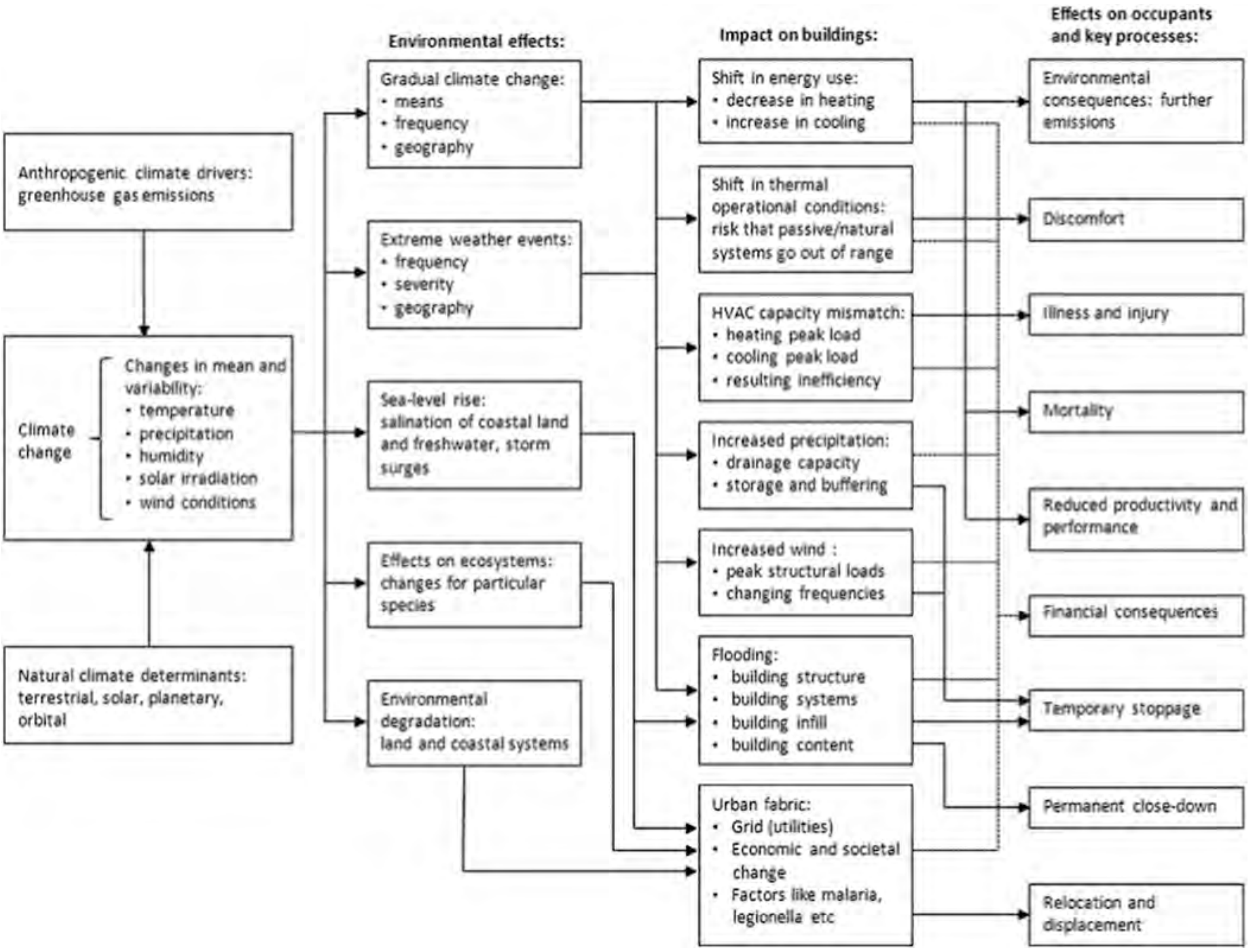

Fig. 13. Climate change impacts on buildings (reproduced with permission [27]).

to the climate resiliency of concrete over its service life by providing resistance to various loads and stressors resulting from climate change occurrences.

Similar to improving the sustainability of concrete, climate resiliency of concrete can be enhanced by designing for high durability for various anticipated applications and local climatic conditions. Climate change impacts have been shown to cause various deterioration impacts on concrete structures such as higher carbonation and corrosion [29,30]. Thus, improving the durability of concrete structures for such deteriorations can be beneficial in improving the climate resiliency of concrete structures. As the durability of concrete is its ability to resist various physical and chemical forces of deterioration/degradation in the environment it is subjected; climate resiliency of concrete can be strongly correlated to concrete durability. Hence, designing and constructing concrete infrastructures for enhanced durability to resist the detrimental impacts of climate changes can be classified as an enhancement of the climate resiliency of the concrete infrastructure.

The need to design climate resiliency for local climatic conditions is due to the high variability of climate conditions based on geographical regions. Countries such as Canada with large areas cannot have a national climate resilience design due to the high variability of climate conditions. For example, Windsor which is the southernmost city of Canada experiences a low amount of snow, however, it is prone to higher floods which could damage various concrete infrastructures. Fig. 14 shows the flood susceptibility index (FSI) for Canada. The darker the blue colour in Fig. 14, the higher the susceptibility of the regions to flooding.

On the other hand, the western parts of Canada such as Vancouver and Alberta are more prone to wildfires which consequentially pose a resiliency threat to various concrete structures. Fig. 15 shows the fire danger in various regions of Canada on August 1st, 2022. The light to dark brown patches in Fig. 15 show the fire history of where wildfires occurred between 1980 and 2020. Thus, a localized approach should be implemented when improving the climate resiliency of concrete structures. The design of concrete structures for enhanced resiliency can be achieved by putting in place policies and guidelines for concrete design and construction and by awareness of the need for climate-resilient concrete structures. Similar guidelines need to be put in place to retrofit old existing structures to adapt to the impacts of changing climatic conditions.

It is also critical to mention that improving concrete sustainability would indirectly improve the climate resiliency of concrete structures as there would be less occurrence of climate change impacts such as extreme heat, flooding, etc. This is evident in the estimated reduction (i.e. approximately 1.5 °C or less) in global temperature (blue colour) with the rapid reduction in CO_2 emissions as shown in Fig. 16. Thus, concrete sustainability and climate resiliency go hand in hand.

Current challenges with the assessment of the impact of durability on sustainability

The assessment of the impact of concrete properties especially the

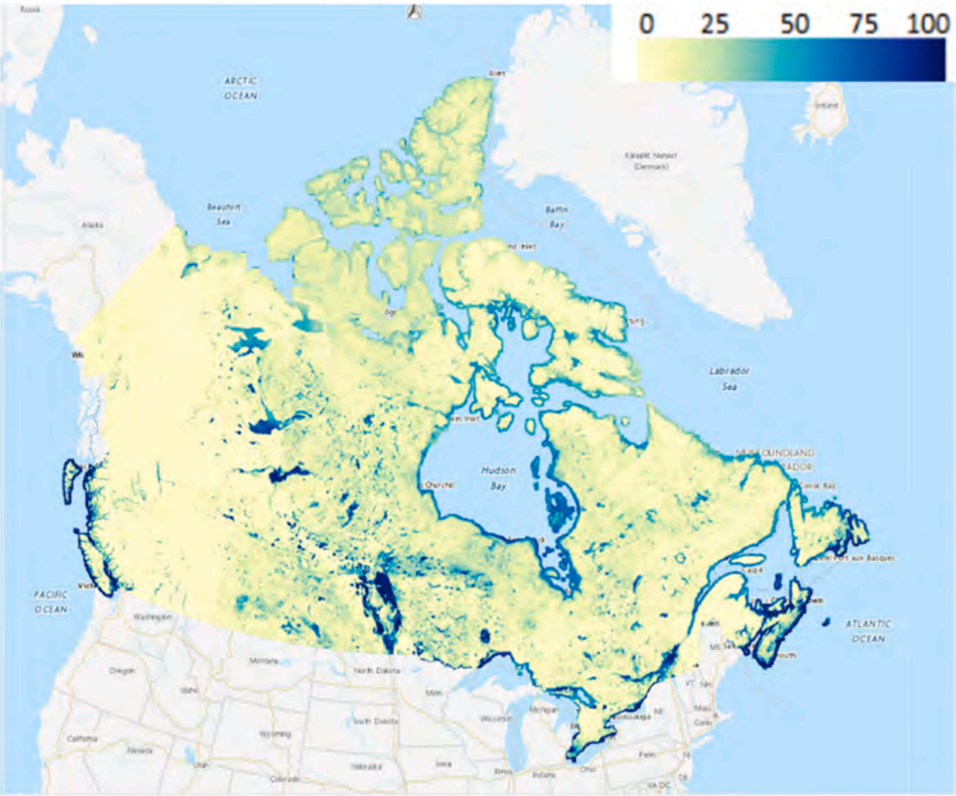

Fig. 14. Flood susceptibility index of Canada
Adapted from [31].

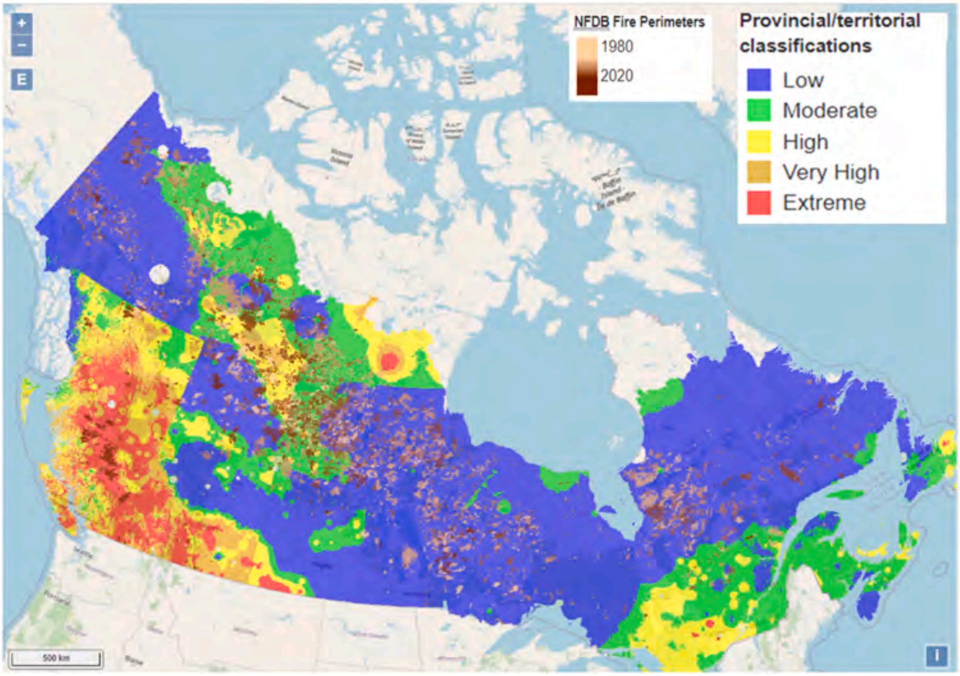

Fig. 15. Wildfire hazard and past wildfires in Canada
Adapted from [32].

durability on sustainability is faced with many challenges that need to be imminently tackled in order to efficiently assess the sustainability of concrete. Some of the major challenges are summarized below:

1. Durability property: there exist many forms of durability properties that can be carried out on concrete and the type carried out is mostly dependent on the application of the concrete. In order to effectively incorporate durability into sustainability assessment, there is a need

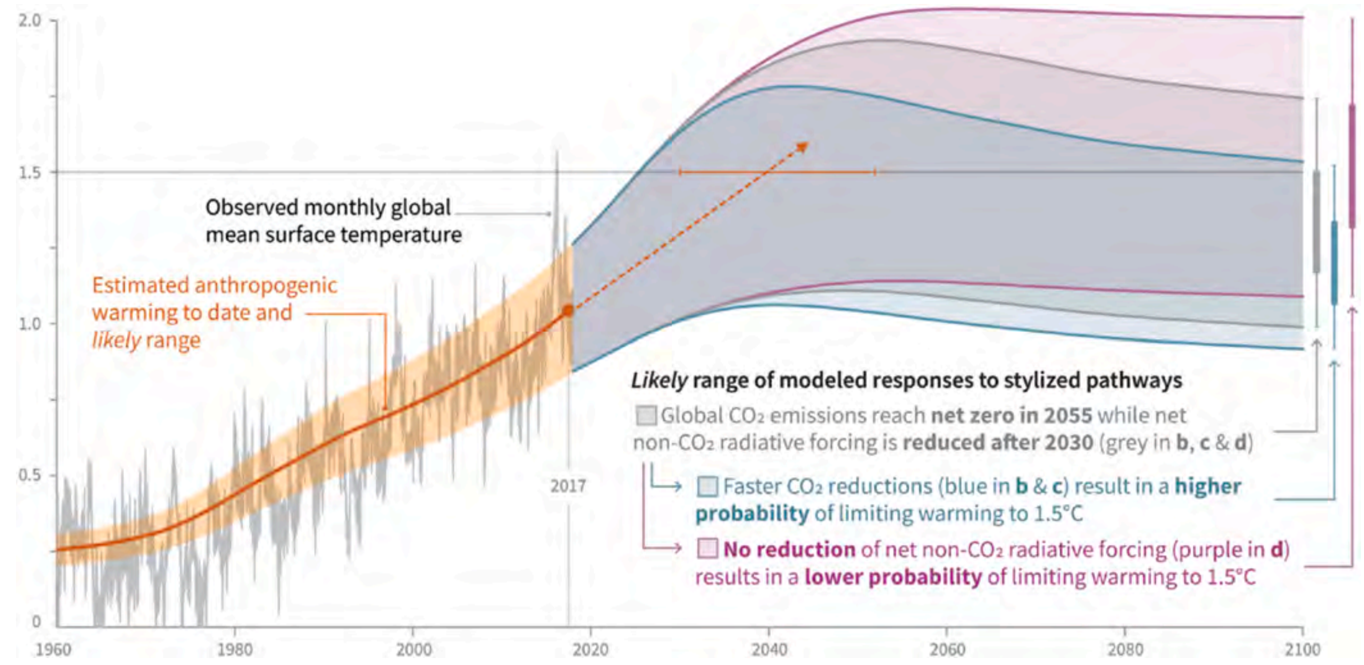

Fig. 16. Global temperature projections with CO_2 reduction scenarios [33].

to use a durability property that is widely used and supported by existing data. Porosity is one of the types of durability tests carried out on concretes. However, the method of porosity assessment varies with standards and sample dimensions. Hence, there is a need to implement specific durability test values to be incorporated into sustainability assessment. Of such test could be the chloride diffusion coefficient which can be correlated to many durability properties such as porosity, chloride ion penetration, sorptivity, etc.

2. Lack of awareness: concrete design is predominately dependent on compressive strength while durability properties or importance is generally neglected. It is critical for more awareness of the influence of durability on the overall service life of concrete.
3. Standards/ guidelines: there is a need for standards and guidelines for the design of concrete sustainability to incorporate durability as one of the requirements rather than only reducing the embodied carbon. Such standards/guidelines can also specify equations to correlate the environmental impacts with sustainability to generate a generalized concrete sustainability index that can be used to accurately quantify concrete sustainability.

Recommendations and Future Studies

1. The majority of the current studies on the sustainability of concrete are limited to the evaluation of only embodied carbon of materials which as mentioned earlier is only a part of the overall sustainability. Hence, there is an imminent need for a more comprehensive assessment such as a life cycle assessment to be carried out in order to accurately evaluate the sustainability of concrete. There is a need for this comprehensive assessment to evaluate the process right from the extraction of the raw material to the recycling/disposal of the concrete structures.
2. Development of a concrete sustainability index which is based on the environmental impacts and performance and can be used to effectively quantify the sustainability benefits of various approaches used to minimize the negative environmental impacts of concrete structures.
3. More collaborations between Government, government departments, industry, research and development and academics. The National Research Council Canada fully understands the critical collaboration between these stakeholders and has actively participated in and promoted such collaborations. However, there is a need for more collaborations globally in order to be able to upscale various innovative solutions to improve the sustainability and climate resiliency of concrete infrastructures.
4. A comprehensive review of the literature also indicates current research and developments revolve around only sustainability where the climate resiliency of concrete is limited. Hence, it is recommended that more studies be carried out to fully understand how the components of concrete and its properties influence the corresponding climate resiliency of the resulting concrete structures.

Conclusion

This paper presents an overview of various properties, specifically the durability of concrete and how it influences concrete sustainability and climate resiliency. Discussions in this paper show that the durability of concrete is very critical to both concrete sustainability and climate resiliency and a holistic approach needs to be employed. Improving the durability of concrete would result in the reduction or elimination of raw material and energy use for rehabilitation and reconstruction resulting in lower environmental impact thereby enhancing sustainability. Similarly, enhanced durability of concrete would ensure that concrete structures can adapt to the changing climate changes thereby improving its climate resiliency.

Thus, to improve the sustainability and climate resiliency of concrete infrastructures; core attention must be placed on the embodied carbon of the materials and the durability performance rather than the former only. Finally, initiatives to improve concrete sustainability and climate resiliency should be specific geographical zone-based rather than a global approach as the availability of raw materials and climate conditions varies with location.

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.

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