**Development of a successive stage hierarchy for rational carbon reduction and resource conservation decision-making in the cement industry**

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## Abstract

The cement industry represents nearly 8% of fossil fuel and industrial emissions making it a key area of focus for policymakers around the world. Much of the current effort in cement manufacturing has focused on energy efficiency and material substitution with more recent work focused on carbon dioxide uptake and recycled concrete aggregate use to address greenhouse gas emissions and material conservation, respectively. Currently, no meaningful approach exists for practitioners or policymakers to address greenhouse gas emission reduction for cement manufacturing that incorporates the concepts of material conservation. The Carbon Hierarchy is proposed as a successive stage hierarchy to address this gap. This work is logically and empirically validated using a newly constructed model incorporating the key levers of service life extension, thermal energy decarbonization, limestone substitution, mineral component (MIC), carbon dioxide uptake with consideration for the process flow that incorporated reintroduction of end-of-life (EOL) concrete as raw material or clinker substitution in cement manufacturing and as potential downstream use as aggregate. The Carbon Hierarchy proposed in this research could guide decisions to significantly reduce greenhouse gas emissions for the cement industry while ensuring material conservation.

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# Introduction

This introduction provides an overview of each of the chapters within this dissertation – explaining the general approach and objectives of each chapter as well as connections between the chapters.

## Chapter 2 – Literature Review

Through a review of academic and industry research, the purpose of this chapter is to reveal whether the need exists for the development of an empirically validated strategy that considers all levers for carbon reduction in a systematic hierarchy while respecting material circularity as a core tenet. The questions posed are as follows:

1) *Does current research in cement lifecycle assessment consider carbon dioxide uptake and material circularity?*
2) *Is carbon dioxide uptake considered as a lever towards a low-carbon cement industry?*
3) *Does a carbon hierarchy currently exist in the cement industry that can prioritize action on greenhouse gas emissions?*
4) *Is current research combining and quantifying circularity and carbon mitigation in the cement industry?*

Answering these questions through a literature review determines the connections and gaps within existing knowledge and the direction of this research. The findings support the development of a successive stage hierarchy to achieve a carbon-neutral, circular cement industry.

## Chapter 3 – Conceptual Model Development, Carbon Hierarchy

The Carbon Hierarchy, a novel approach to prioritizing greenhouse gas emission reduction, is presented in Chapter 3. This new successive stage hierarchy is conceptualized to address the gap, identified in the literature review, that a meaningful support system does not exist for practitioners or policymakers to address greenhouse gas emission reduction for cement manufacturing that incorporates the concepts of material circularity or resource conservation. Ultimately, the concepts of circularity are not captured in the current greenhouse gas decision support systems for cement manufacturing. This leaves a fundamental gap as the concepts of circular economy become more prevalent in policy while climate change remains an environmental policy priority.

The cement industry is specifically chosen as the basis of this model for a number of reasons. Firstly, cement manufacturing represents a significant contribution of greenhouse gas emissions – specifically, 8% of overall global greenhouse gas emissions. Secondly, the unique nature of cement manufacturing is that approximately 60% of greenhouse gas emissions are associated with process emissions – namely, the decarbonation of raw materials that are converted to clinker (the intermediary material resulting from the chemical reaction in the rotary kiln that is the fundamental ingredient in cement). This creates an additional challenge for greenhouse gas reduction since the efficiencies in fuel consumption, a major lever for greenhouse gas reduction, cannot change the decarbonation required to achieve the chemical properties needed to produce clinker and, in turn, cement.

Finally, the cement industry has already identified opportunities to reduce greenhouse gas emissions in various forms that incorporate the concepts of circularity: specifically, the reuse of end-of-life concrete for aggregate or reintroduction to cement manufacturing. However, the cement industry lacks an empirically validated, simplified successive stage hierarchy that identifies how these actions should be prioritized to maximize greenhouse gas emission reduction.

The introduction of a new conceptual model establishes a framework for the following chapters to test the following hypothesis: *"If a successive stage hierarchy for carbon mitigation and material circularity is created it would ensure rational carbon reduction and resource conservation decision making in the cement industry".* Chapters 4 through 7 show that such a successive stage hierarchy can be created and greenhouse gas reduction levers within that system, including circularity, can be used to quantify the gap to reach carbon neutrality.

## Chapter 4 – Analytical Model Development

Greenhouse gas emissions from cement manufacturing are associated with thermal and electrical energy use similar to many other industries. However, approximately 60% of cement manufacturing emissions are associated with decarbonation of raw materials as part of the chemical reaction in the manufacturing of clinker, the intermediary material resulting from the chemical reaction in the rotary kiln that is the fundamental ingredient in cement. Cement carbonates over time, recapturing the carbon dioxide that was released in the chemical reaction of the manufacturing process.

This process has been documented in numerous analyses of concrete samples in lab and real-world application. Further to this, numerous researchers have discussed the potential for reintroduction of end-of-life concrete into cement manufacturing or use as aggregate with a consideration for the total uptake of carbon dioxide by concrete depending on various mixes. Based on the volume of research, there is sufficient data to quantify this unique feature of cement manufacturing in order to accurately capture the benefits associated with carbon dioxide uptake and, more importantly, incorporate that data into a successive stage hierarchy.

The model is unique in that it structures the fundamental inputs required to assess the potential uptake rather than focus on refining the uptake quantification. The formulas in the analytical model are derived to produce a functional mathematical model that allows for the calculation of additive carbon dioxide emissions when end-of-life concrete is reintroduced into cement manufacturing or as an aggregate substitute. This model contributes to the analytical assessment of the carbon hierarchy as it considers the greenhouse gas reduction levers in the cement manufacturing process, the uptake during service life, quantifies the circularity of end-of-life concrete returning to cement manufacturing in the form of carbon dioxide emissions, and potential carbon capture and utilization in aggregates.

The resulting model from this chapter is a synthesis of research structured in a way that allows for the empirical assessment of the carbon hierarchy for cement manufacturing with existing industry data. The model produces an important metric, kilograms of *additive* carbon dioxide per tonne of cement - including the benefits associated with uptake and circularity of cement through numerous lifecycles.

## Chapter 5 – Analytical Model Input and Output Structure

Chapter 5 presents a sample scenario of the model that has been developed based on the formulas presented in Chapter 4 to calculate $CO_2$ uptake by cement during the service life of concrete, reintroduction of end-of-life concrete as raw material and clinker substitution in the cement manufacturing process, and use of end-of-life concrete as aggregate. The chapter includes input and output data, sample formulas, and explanations for the all the aforementioned end-of-life options based on the sample scenarios. This chapter demonstrates the detailed use of the model developed in Chapter 4 that is expanded for numerous scenarios in Chapter 6 and 7.

## Chapter 6 – Generalized Application of the Developed Modelling Approach

Utilizing the model built in Chapter 4, scenario analysis is used to validate the carbon hierarchy structure. In order to assess the value of the carbon hierarchy as a successive stage hierarchy, potential levers for greenhouse gas emission reduction at various levels of the hierarchy are tested individually and in combination. The analysis includes avoidance associated with extended service life and process optimization; industrial symbiosis and material circularity as well as carbon capture and utilization. Combinations of potential greenhouse gas reduction levers that are not mutually exclusive are also assessed to validate the sequential logic of the carbon hierarchy.

The assessment highlights that the carbon hierarchy is empirically logical resulting in reduced additive kilograms of carbon dioxide per tonne of cement at each stage of the hierarchy. The hierarchy further proves empirically logical as greater reduction of carbon dioxide from the base level and maximized natural resource conservation being achieved at the top of the hierarchy. Less benefit is achieved as one moves down the hierarchy. Discussion in this chapter highlights that the additive carbon dioxide levels calculated in various scenarios reflect the current operating conditions of the cement industry. Therefore, as reductions are achieved at the top of the hierarchy there will be fewer available for further reduction. However, the resource conservation remains valid regardless of the incremental improvement at each level of hierarchy. The conclusion drawn, based on the combined additive carbon dioxide and resource conservation, is that the carbon hierarchy is timeless in its application as it reflects a synergistic successive stage hierarchy.

The assessment, however, does highlight a challenge in quantifying industrial symbiosis within the carbon hierarchy as a means of establishing the gap to carbon neutrality. There is a significant benefit achieved in greenhouse gas reductions when substituting cement with cementitious material from other industries such as blast furnace slag, a by-product of the steel industry. The carbon hierarchy itself allows for the inclusion of industrial symbiosis but the quantitative benefit may be misleading without consideration of the original manufacturing environment that produces the by-product. Based on these empirical challenges, specific limitations and considerations are discussed when calculating benefits from industrial symbiosis.

## Chapter 7 – Canadian Application Developed Modelling Approach

Using the model built in Chapter 4 and building off the scenarios in Chapter 6, the additive carbon dioxide emissions are calculated for numerous scenarios applicable to Canada. Scenarios consider the current state of the Canadian industry with respect to cement manufacturing, and potential levers to improve the additive carbon dioxide per tonne of cement through avoidance, stretching, and sequestration (the three levels of the carbon hierarchy).

The assessment results highlight that even with maximum avoidance levels, complete circularity (returning to cement manufacturing) or carbon capture and utilization (as aggregate), the Canadian cement industry will not reach carbon neutrality without implementation of carbon capture and storage. However, using the carbon hierarchy approach and calculating potential uptake results in a significantly lower gap to reach carbon neutrality and confirms that the carbon hierarchy *can be used to quantify the gap to reach carbon neutrality.*

## Chapter 8 – Conclusion & Future Research

The concluding chapter discusses the value and limitation of the carbon hierarchy as well as potential future research to expand on the concept. Ultimately, the value is the creation and validation of a successive stage hierarchy for practitioners and/or policymakers to address greenhouse gas emission reduction for cement manufacturing that incorporates the concepts of circularity. The analytical model allows for empirical validation of the carbon hierarchy and quantifies the gap to reach carbon neutrality for the cement industry.

Further research is recommended in industrial symbiosis in the cement industry, application of carbon hierarchy to other industries, and potential application to media beyond greenhouse gas emissions that may be part of a lifecycle assessment.

# Chapter 2

# Literature Review

This chapter answers the following four questions through a review of academic and industry research to determine whether the need exists for the development of an empirically validated strategy that considers all actions for carbon reduction in a successive stage hierarchy while respecting material circularity as a core tenet.

1) Does current research in cement lifecycle assessment consider carbon dioxide uptake and material circularity?
2) Is carbon dioxide uptake considered as a lever towards a low-carbon cement industry?
3) Does a carbon hierarchy currently exist in the cement industry that prioritizes action on greenhouse gas emissions?
4) Is current research combining and quantifying circularity and carbon mitigation in the cement industry?

## 2.0 Introduction

The objective of this chapter is to review the literature to answer four critical question to guide the research and development of a carbon hierarchy for the cement industry.

Firstly, *does current research in cement lifecycle assessment consider carbon dioxide uptake and material circularity?* This question aims to understand, at a high level, whether carbon dioxide uptake has been studied in order to be empirically assessed as part of the hierarchy as well as whether and how material circularity is considered in such assessments – namely is circularity considered in any research, and if so, in what application(s).

Secondly, *is carbon dioxide uptake considered as a lever towards a low-carbon cement industry?* This question aims to understand whether academic or cement industry research has identified carbon dioxide uptake as a legitimate contributor to reduce the industry's carbon dioxide impact.

Thirdly, *does a carbon hierarchy currently exist in the cement industry that prioritizes action on greenhouse gas emissions?* This question aims to understand whether an explicit priority of actions exists for the cement industry to reduce its GHG emissions. The focus is on the cement industry due to the unique nature of carbon uptake (ie. the ability of cement to reabsorb carbon dioxide).

Finally, *is current research combining and quantifying circularity and carbon mitigation in the cement industry?* This question aims to understand whether there is a convergence of circularity concepts and carbon mitigation strategies in order to support a hierarchical decision-making process.

Answering these questions through a review of existing academic and industry research will determine the nature of the need that exist for the development of an empirically validated strategy that considers all levers for carbon reduction in a successive stage hierarchy while respecting material circularity. The resulting hierarchy could support stepwise decision-making to achieve a carbon-neutral, circular cement industry.

## 2.1 Literature Review

### 2.1.1 LCA and Circularity

*Does the current research in cement lifecycle assessment consider carbon dioxide uptake and material reuse/circularity?*

This question helps determine whether there is an existing body of knowledge that identifies and calculates the full carbon dioxide impact relative to cement manufacturing. If so, this validates that end-of-life purpose is incorporated in lifecycle assessment thinking for cement manufacturing.

Lifecycle Assessment (LCA) is a well-established and recognized process in academic research as well as in industry applications. The process was integrated into the International Standards Organization (ISO) standard – specifically ISO 14040/ISO 14044 with guidance documents published by government agencies such as the ILCD Handbook published by the European Commission (European Commission -- Joint Research Centre -- Institute for Environment and Sustainability, 2010). Due to this acceptance of the method and widespread use, research and industry use of LCA in cement (and by extension, concrete) is widespread. A 2002 World Business Council for Sustainable Development (WBCSD) identified 76 studies directly related to LCA in cement and concrete (Young, Turnbull, Russell, Antonio, & Perez, 2002). Since that time, numerous peer reviewed studies have focused on the use of LCA in cement and concrete manufacturing – of which, more than 30 were directly related to the research conducted in this work. Of these, the following studies focus on carbon dioxide uptake and/or reflect on the material reuse as part of a lifecycle assessment approach.

Carbon uptake inclusion in LCA is prominently featured in research (Christian J. Engelsen & Sæther, 2005; Kikuchi & Kuroda, 2011; Kjellsen, Guimaraes, Nilsson, Knut O. Kjellsen, & Nilsson, 2005; Possan, Felix, & Thomaz, 2016; Zabalza Bribin, Valero Capilla, & Aranda Usn, 2011) with consistent approaches and quantitative methodologies.

Carbon dioxide uptake itself is well documented in research highlighting the potential uptake. For example Possan et al.(2016) state that '*It seems that concrete during its lifetime can uptake from 40 to 90 % $CO_2$ emitted in its manufacturing process*' which is echoed by Kjellsen et al.*(2005) '30% of the total $CO_2$ emission from cement production, or up to 57% of the $CO_2$ emission from the so-called calcination process in cement manufacturing, is re-absorbed when the cement is utilized in concrete construction in the Nordic countries'* . Engelsen et al.(2005) point out that *'75% (of total CaO) is most likely a realistic level of carbonation to be taken into consideration of the total uptake of $CO_2$ to crushed concrete in reasonable time scale (20-50 years) is to be calculated'*

Further to this, two studies highlight that carbon uptake can actually balance the decarbonation process associated with calcination during cement manufacturing. Possan et al. (2016) state that '*In some cases, considering the structure demolition, its uptake is nearly 100%*' while Kjellsen et al. (2005) further specified the recarbonation balance with '*Ultimately, on a very long time scale, all of the CaO will react with $CO_2$ to form $CaCO_3$, so that all of the $CO_2$ liberated by calcination during cement manufacture will be reabsorbed*'.

Perhaps the most comprehensive study of carbon dioxide uptake was performed by Xi et al., (2016). This study concluded that 43% of the carbon dioxide emissions from the production of cement (excluding fossil fuel use) are sequestered in existing structures, demolished material, or by-products. This highlights the potential value of assessing carbon dioxide uptake at a macro level and inclusion of uptake in LCA.

In most scenarios of lifecycle assessment, carbon uptake calculations extend into a discussion of material reuse as the end-of-life portion of the assessment either to substitute road base or fill material. This is a common approach but also highlighted by some researchers as a problem as the only outlet being low value application – so material reuse is considered but not circularity *per se*. De Schepper et al. (2014) highlight the magnitude of the material challenge:

> *Since the construction sector uses 50% of the Earth's raw materials and produces 50% of its waste, the development of more durable and sustainable building materials is crucial. Today, Construction and Demolition Waste (CDW) is mainly used in low level applications, namely as unbound material for foundations, e.g., in road construction.*

Kjellsen et al. (2005) further highlight that the final destination of aggregate also impacts the rate that carbon dioxide will be reabsorbed by the material. Specifically, in Nordic countries, the crushed concrete is "*used in below ground application, where the rate of carbonation is lower than in above ground applications.*"

De Schepper et al. (2014) reinforce the previously highlighted uptake potential in applications of LCA '*concrete is able to capture $CO_2$ from the atmosphere, which can be seen as a benefit when performing a Life Cycle Assessment*' but highlight the gap in assessment as "*…this $CO_2$ capture from the atmosphere was not considered within the traditional recycling scenario*'. Vieira et al. (2016) expand on De Schepper's et al. (2014) point, acknowledging that the end-of-life material could be used in new concretes, '*The need for further LCA studies on the treatment and reuse of construction waste is evident to prevent its disposal in the environment and to incorporate it in the life cycle of new concretes*'

The study by De Schepper et al. (2014) is quite relevant to this work as the focus is on a concept named "Completely Recycled Concrete" – in other words, complete recycling of concrete to be returned to a cement plant for reintroduction as raw material fundamentally closing the loop of cement manufacturing.

> *CRC (*completely recycled concrete*) becomes a resource for cement production because the chemical composition of CRC will be similar to that of cement raw materials. If CRC is used on a regular basis, a closed concrete-cement-concrete material cycle will arise, which is completely different from the current life cycle of traditional concrete.*

The De Schepper et al. (2014) study results show that 't*he main environmental benefit of CRC recycling is related to its global warming potential*'.

There is a clear benefit for the active inclusion of carbon dioxide uptake in lifecycle assessment of cement and a drive towards material circularity with one study. De Schepper et al. (2014), fully examining it. Further to identified carbon dioxide reduction in lifecycle assessment, the following sections examine the degree to which this concept has been highlighted as a potential lever for the cement industry to lower its carbon footprint.

### 2.1.2 $CO_2$ Uptake as a Lever

*Is carbon dioxide uptake considered as a lever towards a low-carbon cement industry?*

Carbon dioxide uptake is referenced as a carbon sink, recarbonation in concrete, or as Carbon Capture & Utilization (CCU) referring to the carbonation of crushed concrete for use as aggregate (Cembureau, 2013; Global $CO_2$ Initiative & $CO_2$ Sciences Inc., 2016). The Concrete Council of Canada has explicitly identified this as one of three key strategies highlighting the need for '*deep investments in potentially transformative technologies such as carbon capture and reuse to transform concrete into a carbon sink*' (Concrere Council of Canada, n.d.)

Mikulčić et al. (2009) explain the potential of a carbon sink in concrete '*$CO_2$ from the atmosphere penetrates concrete and reacts with calcium hydroxide in the presence of moisture to form calcium* *carbonate, a process called carbonation. Thus, concrete could serve as a sink for $CO_2$ sequestration'.* Zabalza et al. (2011) go further to capture the concept of aggregate substitution and the continued carbon dioxide uptake through the second life of the material, highlighting the importance of this for carbon intensive material:

> *'…materials with significant $CO_2$ emissions, such as concrete, can see their emissions reduced by giving them a second life as a filler material in infrastructure, with a double effect: the reduction of emissions compared with obtaining filler materials from quarries and the absorption of $CO_2$ due to the recarbonation processes.'*

Xi et al. (2016) in the global assessment of carbon dioxide uptake of existing concrete structures went even further to clearly state the need to maximize the recarbonation as a key lever in combating climate change:

> *'Finally, policymakers might productively investigate ways to increase the completeness and rate of carbonation of cement waste (for example, as a part of an enhanced weathering scheme) to further reduce the climate impacts of cement emissions.'*

This statement by Xi et al. (2016) highlights the need to maximize uptake that adds to the existing approach of reducing emissions from production. In combination, this highlights the need to assess all potential steps to minimize emissions to further reduce the gap between emissions and recarbonation. The Portland Cement Association (PCA) (2019) concisely states the recommendation that *'we should be open-minded to the concept that concrete may also serve as a carbon dioxide sink with the potential to balance some of the releases in its manufacture'.*

The following section aims to understand whether such a holistic assessment has been completed and, if so, whether the impact options have been ordered in some type of hierarchical fashion to support decision-making.

### 2.1.3 Existing Carbon Hierarchy

*Does a carbon hierarchy currently exist in the cement industry that prioritizes action on greenhouse gas emissions?*

The theme researched here is whether existing publications outline an explicit priority of actions for the cement industry to reduce its GHG emissions including not only the levers needed to reduce GHG emissions but the order for adopting such levers. Non-governmental and industry organizations have published strategies to achieve low-carbon cement production and/or utilization with the international organizations identifying the key levers to deliver the needed results. For example, Cembureau (2013) identified five initiatives as part of "The Role of Cement in the 2050 Low-Carbon Economy" including: Resource Efficiency; Energy Efficiency; Carbon Sequestration and Reuse; Product Efficiency; and Downstream (referring to the environmental benefit achieved through the use of cement product). Further, The International Energy Agency (IEA) (2009) with the World Business Council for Sustainable Development (WBCSD) identified four technology opportunities to reduce $CO_2$ emissions in the "2009 Cement Technology Roadmap" including: Thermal and electrical efficiency; alternative fuels; clinker substitution; and carbon capture and storage.

The World Wildlife Fund (WWF) International report authored by Muller & Harnisch (2008) identified six key actions to reduce emissions from cement manufacturing outlined in "The Blueprint for a Climate-Friendly Cement Industry" including: use cement more efficiently; further expand the use of additives and substitutes to produce blended cements; improve the thermal efficiency of kilns; improve the electrical efficiency of plants; increase the share of biomass in the fuel mix; and develop carbon capture and storage.

The above-mentioned reports outline detailed strategies and quantify potential benefits of each lever but stop short of highlighting how actions could be prioritized in a hierarchical manner.

Some academic research presents key levers or impacts similar to the aforementioned international position papers. In general, Ammenberg et al. (2015), Uson et al. (2013), and Benhelal et al. (2013) highlight similar actions to those expressed by Cembureau, IEA, and WWF without specification to the order of actions. Others do go further to highlight specific areas of priority with a thought towards hierarchical priorities.

Xi et al. highlighted the need to prioritize fossil-fuel emission reductions over calcination emission reductions due to the uptake potential as follows, '*efforts to mitigate $CO_2$ emissions should prioritize the reduction of fossil-fuel emissions over cement process emissions, given that produced cement entails creation of concomitant carbon sink*' (Xi et al., 2016). This is an important statement as it highlights a priority not due to the potential carbon dioxide reduction quantity, availability of technology, or cost of implementation but rather due to the potential to address calcination emissions through uptake that is not possible with fossil-fuel use.

Both organizational position papers and academic research consistently highlight that efficiency within the operation alone represents only a portion of the potential carbon dioxide emission reductions as exemplified by Ammenberg et al. (2015):

> *' …it is crucial to remember that "in-side-the-fence measures" have a limited potential, because the commonly high clinker content is bound to the calcination process, typically causing more than 50% of the total $CO_2$ emissions…it is the single most important source of $CO_2$ and that process is not affected by measures addressing the production efficiency.'*

and further look to existing tools such as lifecycle assessment, encouraging quantification to support decision-making by Gabel, Forsberg & Tillman (2004):

> *'Many of these solutions have consequences outside the actual cement manufacturing plant, both upstream as well as downstream. Therefore, the life cycle perspective is necessary to assess the environmental consequences of process and production changes in order to avoid sub-optimisation.'*

Hasanbeigi & Springer (2019), referencing California's cement industry, present an order where CCUS is highlighted as the most significant lever for $CO_2$ emission reduction:

> *'Carbon capture utilization and storage (CCUS) could make the largest contribution to $CO_2$ emissions reduction in California's cement industry through 2040, followed by clinker*

*substitution (i.e. replacing clinker with SCMs in cement or in concrete) and fuel switching. Energy efficiency (EE) technologies provide additional $CO_2$ emissions reductions potential.'*

This is echoed by Xu et al. (2016) in a preceding study, stating that *'CCS technology is necessary for the cement industry to achieve stringent emission reduction targets'.*

While Hasanbeigi & Springer (2019) imply an order to the $CO_2$ emission reduction potential – the order consistently presented throughout the publication is energy efficiency following by clinker substitution then fuel switching and finally by CCUS. Although the order for the first three is not explicitly highlighted, CCUS is last as the technology is not as readily available as it is for the first three.

The studies reviewed have not explicitly stated a hierarchy, however, in many there is an implied order. Unfortunately, it is unclear what is the rationale for the order is or how specific jurisdictions or jurisdictional actors would make decisions based on an order. Cembureau's (2013) report goes further to clearly state that the 2050 Roadmap is based on *'5 parallel routes'* - steering clear of a hierarchical approach to implement these levers.

This section has focused on the potential existence of a carbon hierarchy which, although is lacking, could be synergized from existing research. What remains to be understood is whether carbon mitigation and circularity converge in any of the research. The following section outlines where the concepts of carbon mitigation and circularity are beginning to overlap in cement/concrete research and areas where some researchers are looking to marry the concepts to achieve sustained environmental benefit from a material conservation and carbon mitigation standpoint.

### 2.1.4 Combined Carbon Mitigation and Circularity

*Is current research combining and quantifying circularity and carbon mitigation in the cement industry?*

Research referenced in Section 2.1.1 through 2.1.3 demonstrates the use of lifecycle assessment including carbon dioxide uptake in the cement industry, the identification of uptake as a lever, and the development of carbon strategies with thoughts towards the establishment of a hierarchical structure to support decision-making. The final question in this literature review is to understand whether there is a convergence of circularity concepts and carbon mitigation strategies in order to support a hierarchical decision-making process.

As stated in previous sections, the work by De Schepper et al. (2014) has established a circular material system option for the cement industry and the work has identified that '*the main environmental benefit of CRC recycling is related to its global warming potential'*. The fact that global warming potential is the main benefit reinforces the opportunity to further expand on the concepts of CRC in a more holistic model.

Unlike De Schepper et al. (2014), the work by Atsonios et al. (2015) focused on the cement manufacturing process circularity. More specifically referring to a system called "Calcium Looping" in which $CO_2$ recarbonates by-products of the cement manufacturing process. This serves as another example of circularity concepts supporting carbon mitigation strategies.

Circular economy thinking such as industrial symbiosis or, more broadly industrial ecology are highlighted in research showing that consideration is being given towards the adoption of these principles in the quantification of environmental impact. Lifecycle assessment could be a tool to support better decision-making not only within an industry but to facilitate material exchanges between industries (Aid, Brandt, Lysenkova, & Smedberg, 2015) but this comes with clear challenges of quantifying and allocating impact and benefit across industries (Chen, Habert, Bouzidi, & Jullien, 2010). Even when quantification or allocation is achieved in the research, there is an acknowledgement of potential benefits:

> *The use of alternative fuels in the cement industry entails an energy assessment of different types of waste, which would otherwise end up in a dump or incinerator, causing a higher environmental impact. This assessment means waste can be converted into resources, helping to close the cycle of the materials, a key concept for reaching a true industrial ecology.* (Zabalza Bribin et al., 2011)

Other key principles of circular economy, primary 'cradle-to-cradle' (McDonough & Braungard, 2002), are being referenced in research focused on the cement industry. Vieira et al. (2016)highlight the interest of moving towards established circular economy principles such as cradle-to-cradle in lifecycle assessment in the cement industry: '*Although the most commonly used boundary is the cradle-to-gate, the tendency is to advance to the cradle-to- cradle approach'*. Di Maria et al. (2018) reinforce the cradle-to-cradle thinking referring to low-value use of end-of-life concrete as fill: '*Recycling in such low-value applications can be labeled as downcycling, that is the practice of using recycled material for an application of less value than the original purpose of the material'*.

Although the concepts of circular economy are discussed throughout the cement industry, material circularity similar to what is identified in the De Schepper et al. (2014) study is not extensively considered but could potentially be captured under the category of 'raw material substitution' (Cembureau, 2013; International Energy Agency, 2009). It is important to highlight that although circularity has not been explicitly identified as a strategy, the concept of 'raw material substitution' is identified as a lever towards a low-carbon cement industry through reduction of virgin resource use. However, there is currently no work that explicitly establishes circularity boundaries or guidelines in either lifecycle assessment or quantified carbon mitigation options for the cement industry.

## 2.2 Conclusion

The use of LCA and consideration of material reuse is quite widespread, but the latter is not consistently considered or connected to LCA. Carbon dioxide uptake is clearly an area of interest and is identified as an area of carbon reduction. Numerous carbon mitigation strategies are identified for the cement sector with some reference to prioritization, however, the rationale for the prioritization is not clearly quantified. Finally, circularity concepts are identified and in one example even quantified for carbon reduction.

The review of existing research highlights that the key concepts, strategies, and calculations have been identified for both carbon mitigation and circularity in the cement sector. What is fundamentally missing is an empirically validated strategy that considers all levers for carbon reduction in a systematic hierarchy while respecting material circularity as a core tenet. The resulting hierarchy could support stepwise decision-making to achieve a carbon-neutral, circular cement industry. As such, the work is presented in the remaining chapters to answer the following research question:

*If a successive stage hierarchy for carbon mitigation and material circularity is created, would it ensure rational carbon reduction and resource conservation decision making in the cement industry?*

# Chapter 3

# Conceptual Model Development

# Carbon Hierarchy

The following chapter presents a conceptual model of a decision support system for carbon mitigation and circularity to ensure rational carbon reduction and resource conservation in the cement industry. The conceptual model is developed to address an existing gap in consistent decision- making to achieve the transition to a low-carbon, circular economy. The cement industry is chosen as it represents a key contributor to global greenhouse gas emissions and material consumption while remaining a critical material for development with increased projected utilization worldwide through 2060.

### 3.0 Introduction

The International Panel for Climate Change (IPCC) reported in 2018 that manmade greenhouse gas emissions must be reduced to net zero levels by 2050 to avoid irreversible impacts associated with a global temperature increase of two degrees Celsius above pre-industrial levels (IPCC, 2018; UNFCCC, 2019). The cement industry represents nearly 8% of fossil fuel and industrial emissions making it a key area of focus for policymakers around the world (OECD/IEA and The World Business Council for Sustainable Development, 2010) (Portland Cement Association, 2013)

Policy initiatives and technologies within the cement sector have been identified to reduce the $CO_2$ emissions associated with cement manufacturing. Cembureau has identified five initiatives as part of "The Role of Cement in the 2050 Low-Carbon Economy" including: Resource Efficiency; Energy Efficiency; Carbon Sequestration and Reuse; Product Efficiency; and Downstream (referring to the environmental benefit achieved through the use of cement product) (Cembureau, 2013). The International Energy Agency (IEA) and the World Business Council for Sustainable Development (WBCSD) identified four technology opportunities to reduce $CO_2$ in the "2009 Cement Technology Roadmap" including: thermal and electrical efficiency; alternative fuels; clinker substitution; and carbon capture and storage (OECD/IEA and The World Business Council for Sustainable Development, 2010). In addition, the IEA and WBCSD identified several cements in the start-up phase that may substitute traditional cement completely with significantly lower or negative $CO_2$ emissions (OECD/IEA and The World Business Council for Sustainable Development, 2010). The World Wildlife Fund (WWF) International identified six key actions to reduce emissions from cement manufacturing outlined in "The Blueprint for a Climate-Friendly Cement Industry" including: use cement more efficiently; further expand the use of additives and substitutes to produce blended cements; improve the thermal efficiency of kilns; improve the electrical efficiency of plants; increase the share of biomass in the fuel mix; and develop carbon capture and storage (WWF International, 2008).

In general, these agencies are presenting similar levers for emissions reductions with some nuance in the terminology or grouping of actions – namely: the efficient use of resources (material and energy resources including alternative fuels and feeds); carbon capture and storage, and invention of new cement making processes completely. Other research to reduce the carbon intensity of the cement industry is also focused within these general categories as presented in Chapter 2.

These levers have the potential to significantly reduce if not completely eliminate $CO_2$ emissions from the cement industry, but not without a significant reliance on carbon capture utilization and storage (Hasanbeigi & Springer, 2019; Portland Cement Association, 2019; Xu, Yi, & Fan, 2016). The challenge lies in the lack of consistency of the sequence to make such implementation decisions. As a capital-intensive industry, the cement industry must make informed decisions before enacting change where investments may not produce the desired returns.

This chapter proposes a paradigm shift in the approach to addressing carbon emissions from cement manufacturing. The goal is to better prioritize decision-making for greenhouse gas emission reduction by proposing a hypothetical framework by which to make decisions on emerging technologies and policy ideas. Chapters 4 through 7 will empirically test this hypothesis as it applies to the cement industry.

## 3.1 Carbon Uptake & Circular Processes

### 3.1.1 Carbon Uptake

An important notion that has in recent years been addressed in academic research and industry publication is that of carbon uptake – or carbon capture and utilization. Some key examples of these developments includes the direct injection of $CO_2$ in concrete (Concrete Cure, 2019); the uptake of $CO_2$ in concrete as cement carbonated within existing infrastructure (Xi et al., 2016); and the potential uptake of carbon dioxide in crushed concrete used as aggregate (Global CO2 Initiative & CO2 Sciences Inc., 2016; Kjellsen, Guimaraes, Nilsson, Knut O. Kjellsen, & Nilsson, 2005; Possan, Felix, & Thomaz, 2016).

Carbon dioxide uptake is clearly an area of interest and is identified as an area of carbon reduction. As demonstrated in Chapter 2, numerous carbon mitigation strategies are identified for the cement sector with some reference to prioritization; however, the rationale for the prioritization is not clearly quantified.

## 3.2 Moving Towards a Circular Industrial Process

The concept of 'waste equals food' is not new in research or application (McDonough & Braungard, 2002). The idea is that one industry's by-product becomes the feedstock for another industry. The cement industry has been involved in this to a significant extent with the use of waste-derived fuels for clinker production, substitution of raw materials with mineral wastes or contaminated soils, the substitution of cement with blast furnace slag, the substitution of cement with fly ash from coal power generating stations, and the use of synthetic gypsum from the desulphurization systems of power generation stations. (Cembureau, 2013) (WWF International, 2008) However, what has received limited attention is the use of cement at the end of the useful life of the product, concrete, and its ability to play a vital role in a circular industrial process (De Schepper, Van den Heede, Van Driessche, & De Belie, 2014). The primary focus has been on one of two applications – reintroduction of recycled aggregates as substitution for virgin aggregate or the use of unreacted cement paste as a potential for carbon sequestration. (Cembureau, 2013) (Young, Turnbull, Russel, 2002) (Iizuka, 2004)

However, re-use of concrete as an aggregate is actually downcycling (Di Maria, Eyckmans, & Van Acker, 2018). This is a process defined by McDonough and Bruntgard in Cradle-to-Cradle where a high value product is reutilized for a lesser purpose – never to be reused to the benefit of same economic, social, or environmental value as its ingredients. (McDonough & Braungard, 2002) This is not to suggest that the reuse of crushed concrete as aggregate has a negative impact on the environment; but rather that a circular economy cannot be achieved if products are downcycled without consideration of the potential to circulate the material first.

The concept of a "circular industrial process" is being proposed here as a goal that would render an industrial process benign to the environment – with the specific focus on zero net additive greenhouse gas emissions. A circular industrial process must reach zero net additive greenhouse gas emissions without the consideration of comparisons to other processes or as a substitute to other materials being considered towards the emission benefit. As such, the efficiency achieved by using one material over another during the useful life of the material cannot be taken into account as such accounting presumes that the in-use inputs or other industrial processes remain static. This concept is derived from McDonough and Bruntgard's concept of focusing on materials that are "more good" rather than "less bad". (McDonough & Braungard, 2013). A material, and ultimately the process that creates it, must be beneficial to the environment; however, as a concept of a circular industrial process it must be a closed loop so that zero net additive emissions are created.

Process boundaries are critical when evaluating the potential of a circular industrial process. Not all industries have the same potential to reach this goal and cement could be one of the most challenging. However, based on the current global impact of cement to carbon emissions, it is one of great importance. The achievement of a circular industrial process results in not only the relief of pressure on the environment from the tremendous $CO_2$ contribution of cement manufacturing. If cement manufacturing can become a circular industrial process, then the quantity of its $CO_2$ emissions is irrelevant as these would not be additive.

The Carbon Hierarchy, presented in the following section, outlines the role that a circular industrial process can play in the achievement of $CO_2$ emissions reductions and how such a concept can exist within a framework of reducing overall additive carbon dioxide emissions in the cement industry.

Circular industrial processes, however, are not necessarily consistent with greenhouse gas reductions. The reprocessing of a material for future use may be more greenhouse gas intensive than producing the product from virgin raw materials. As such, the carbon hierarchy must also be consistent with natural resource conservation. The carbon hierarchy provides a decision-making approach that must be structured to reduce greenhouse gas emission while respecting the conservation of natural resources. The next section expands on the concept of the carbon hierarchy and the appropriate order as well as conditions to minimize greenhouse gas emissions while respecting the conservation of natural resources.

### 3.3 The Carbon Hierarchy

As with the waste hierarchy, the proposed carbon hierarchy is introduced to shed light on the opportunity to create solutions at each step of the hierarchy. Figure 3.1 compares the existing Waste Hierarchy to the proposed Carbon Hierarchy to highlight the similarities.

In both hierarchies, the objective is to move from top to bottom in terms of process and product design as each step downwards results in a greater environmental burden. However, it is important to highlight that each step has merit and that proper disposal (or sequestration) has its place in the hierarchy. Waste management has evolved to include a hierarchy that is accepted within policy and adapted for use by other organizations driving waste reduction initiatives (Environmental Commissioner of Ontario, 2017; Zero Waste Canada, 2018). The simplicity and logic of the waste hierarchy allows for such a continued use of the hierarchy. Carbon dioxide or carbon (as referred to here for simplicity of nomenclature) has not evolved to include such a hierarchy – it remains at the periphery of the solution, namely with avoidance or sequestration as seen in the aforementioned reduction levers of the WBCSD, WWF, and Cembereau (Cembureau, 2013) (WWF International, 2008) (OECD/IEA and The World Business Council for

Sustainable Development, 2010). As such, when compared to the waste hierarchy the current focus remains on reduction or disposal – which would not be accepted in current practices in waste management but remains the focus in carbon management. Further to this, most carbon is simply released – or in terms of waste management, "uncontrolled dumping". Figure 3.1 presents the Carbon Hierarchy with comparison to the waste management hierarchy.

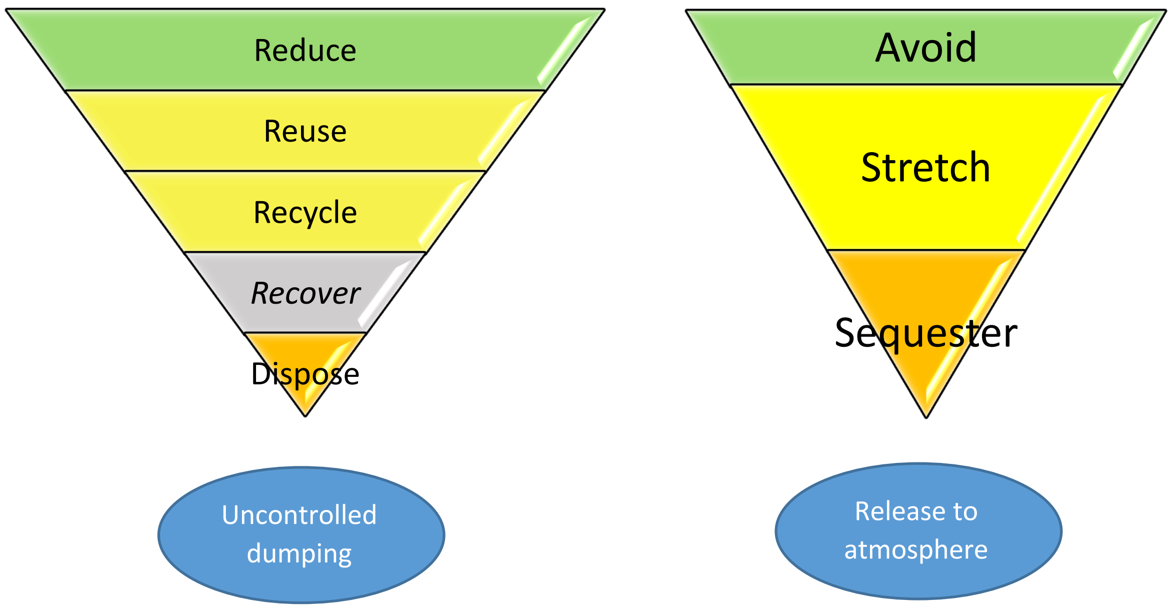


Figure 3.1: Waste Hierarchy (five stage – four stage would exclude 'recovery'); Carbon Hierarchy

Figure 3.2 shows a more detailed breakdown of the carbon hierarchy that provides the sequence and structure of each level of hierarchy.

This is the missing narrative to carbon dioxide management as a multilevel approach. Reflecting on the emergence of the waste hierarchy, there is a narrative that resonates with operators and policymakers as demonstrated with the key jurisdictions, such as the US and EU, that have adopted a nearly identical hierarchy (European Commission, 2008; US EPA, 2020).

It is clear that action to minimize the impacts of climate change is necessary but competing narratives and potential unintended consequences on other environmental systems may be difficult for individuals and, even more so, industry to prioritize and put into action. An individual industry may not have the technological capability to eliminate their carbon dioxide emissions - as such, should their immediate reaction be an investment in carbon sequestration? This may be the simplest solution (whether economically or technologically sound) but this would be the equivalent of the following statement "once you've reached the limits of reducing your waste, dispose of the rest." This type of approach would not be logical based on what we know of waste management, the opportunities to reuse materials, recycle or even recover prior to disposing of those resources. The carbon hierarchy can act in much the same way to allow industries and businesses to design their products and processes such that the elimination of carbon emissions is achieved first, once exhausted then stretch[1] the carbon usage through industrial symbiosis or material circularity, and finally look to carbon capture utilization and

[1] Carbon stretching is a novel concept explained in detail in Section 3.2

storage (as presented in Figures 3.1 and 3.2). The first and second stage, approached in parallel, can reduce the need for carbon sequestration and meet the needs of climate change reduction as a movement to a low-carbon economy. Ultimately, the uncontrolled release of carbon needs to be eliminated, but there should be a movement to maximize each stage of the hierarchy to minimize the amount of carbon that requires sequestration. Industry should look to this as an iterative process where all levels of the hierarchy are continually evaluated. This is to say, as exemplified by the waste hierarchy, that simply because a material is being recovered or recycled does not mean that an option for reuse or reduction should be ignored.

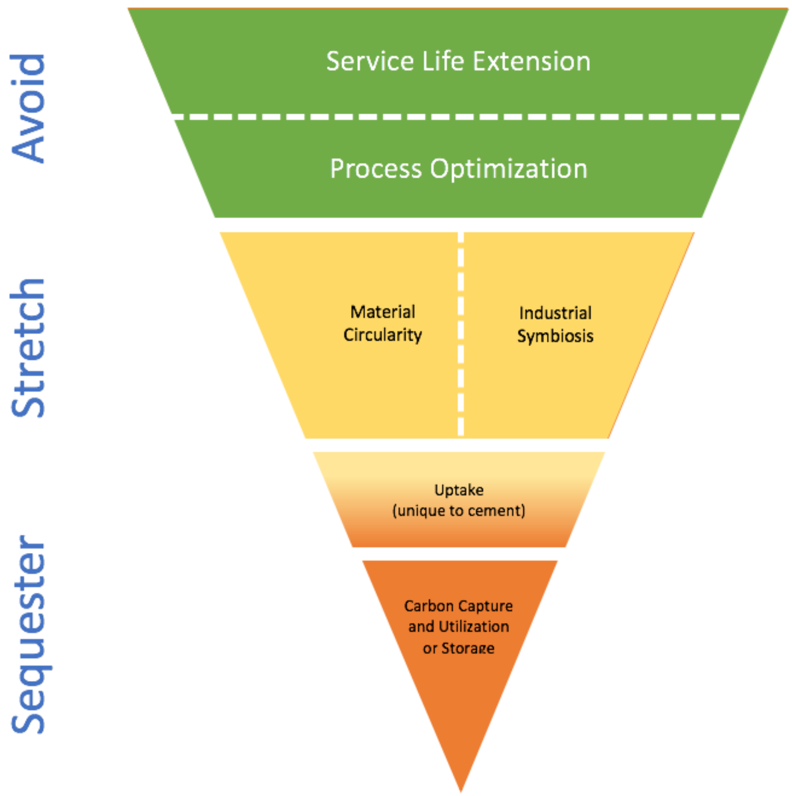


Figure 3.2: Proposed Carbon Hierarchy

The following sections provide further explanations and examples of each stage of the carbon hierarchy.

### 3.3.1 Avoid [*Reduction*]

Avoidance is the complete elimination of carbon release. This is the most logical step in the carbon hierarchy – it is the reduction of carbon release through efficiencies, process changes, and design upgrades. This is where much of the current effort is focused. This stage encapsulates improvements in energy efficiency, energy decarbonization, and extended material life. This stage has the potential to reduce the amount of carbon that needs to be stretched or sequestered.

The most logical example of avoidance is the extension of service life resulting in the reduction of carbon emissions, as the product would not have to be made in the first place. Life extension must consider the longevity of a product versus carbon emissions associated with the production of a longer lasting product; for example, extending the life of a material by 50% while increasing the carbon emissions for that material by 51% or greater to achieve the longer life is not logical.

The second manner of avoidance is through the reduction of thermal or electrical energy consumption: in other words, process optimization. Process optimization and energy decarbonization can be considered to be synonymous in the carbon hierarchy, understanding that the limitation is the availability of renewable energy sources for electricity or thermal needs. It is important to include both options in the carbon hierarchy as some processes, including cement production, require a specific amount of energy inputs to achieve the desired chemical reactions, so decarbonization is the more rational lever once minimum thermal inputs have been reached.

Avoidance is the simplest to calculate as it represents a direct reduction. However, avoidance requires considerable redesign of the existing systems. Some of these redesigns are logical and require limited intervention such as energy efficiency. Energy efficiency, whether in industrial or domestic applications, is quite logical as energy - whether heat energy or electrical energy, is directly connected to cost of operations - the cost of manufacturing a product, operating an office building, or comfort living. Avoidance has, and continues to be, the primary focus within the manufacturing sector.

### 3.3.2 Stretch [*Reuse/Recycle*]

Carbon stretching is a novel concept being introduced here. To this date (based on the author's research) this concept does not exist in current research or industry literature. The concept is not dissimilar to those introduced in Circular Economy thinking in that it considers beneficial aspects of circular production systems versus linear ones such as reduced waste generation and material extraction (Ellen MacArthur Foundation, 2019). However, these concepts will not guarantee the reduction of greenhouse gas emissions without a robust structure to evaluate carbon reduction decisions, hence the need for a carbon hierarchy.

Stretching can be divided into two general categories – namely, material circularity and industrial symbiosis. These processes are distinct as one is internally focused (the producer receives the material for reprocessing to reduce carbon emissions) versus externally focused (a by-product of another industry is utilized to reduce carbon emissions).

Material circularity is defined here as returning end-of-life materials to the same process as was used to manufacture the material in the first place. Depending on the end-of-life material, this may reduce the greenhouse gas emissions associated with the production, but it should not be taken for granted that a reduction is guaranteed. Material circularity will certainly result in the reduction of waste generation as well as raw material extraction. In cement applications, material circularity results from end-of-life concrete being returned for the manufacturing of new cement.

Industrial symbiosis is the use of material from another industry rather than disposing of the material from the one industrial process and extraction of virgin raw material for the other industrial process. Fundamentally, the carbon emission has not been avoided but through carbon stretching, additional carbon is not released. One examples of this in the cement industry is the use of slag, a by-product of iron making, as a cement substitute. Slag has to go through its own thermal process to produce a material of value to the cement industry but can displace the need for traditional cement. Fly ash, a by-product of coal-fired electricity generation, is another example of industrial symbiosis where the product displaces the need to manufacture traditional cement but only exists as a result of coal-fired powerplants.

Unlike circular economy principles, the carbon hierarchy does not place material circularity above industrial symbiosis (fundamentally functioning as a result of waste generation) but rather alongside one another. The rationale for this is that depending on a product's markets where more material demand exists than the stock that is available to circulate – industrial symbiosis could play a critical role in offsetting the increased material demand or associated carbon emissions with increased production needs. This is a particularly valid example for the cement industry as the demand for building materials will continue to grow through 2060 (OECD, 2019), so numerous options in the carbon hierarchy will need to be exercised. However, the availability of slag as a cement substitute can reduce the need for increased production of cement.

Stretching is fundamentally different from avoidance as the reduction is only related to the secondary beneficial use of the material for which carbon dioxide was released to create in the first place. It is important to note that stretching is a partial reduction while avoidance is a complete reduction, hence the order.

### 3.3.3 Stretching with Uptake (unique to the cement industry)

Stretching with uptake is a concept that straddles stretching and sequestration. It refers to the uptake of $CO_2$ during the carbonation of cement. This concept is explained in detail and empirically tested as a key influencer in the structure of the carbon hierarchy as presented in future chapters. The reason that uptake straddles stretching, and sequestration is that uptake occurs during the service life of concrete through the recarbonation of cement. However, the use of end-of-life concrete determines whether the action is defined as stretching or sequestering.

### 3.3.4 Sequester *[Dispose]*

Carbon Sequestration, much like waste disposal, is the responsible way of managing unwanted by-products of production or use. Carbon sequestration can be considered a disposal of the carbon. It is managed beyond the point of production or use. This would be considered only for carbon sequestration that is done for the purpose of removing carbon from a process or the atmosphere but would not have any beneficial uses during the process of sequestration. As such, the use of carbon capture for a beneficial purpose would hold a higher position on the hierarchy. For example, carbon that is captured in concrete that is used as aggregate (creating a useful product) would be higher on the hierarchy than carbon that is captured by the same material but then sent to landfill. The latter example does not respect natural resource conservation and assumes an unbounded system of infinite material or disposal space. The same is true of carbon capture and subsurface storage as it assumes an infinite amount of space to contain the carbon.

Carbon release (ie. the net addition of carbon to the atmosphere) is not considered part of the hierarchy. This is based on the concept that even disposal is a technical solution to waste management. Although incineration and landfilling may be the last options of the waste management hierarchy, these still remain as viable technical options to manage waste responsibly. In comparison, uncontrolled dumping without properly engineered solutions is an irresponsible way of managing waste. This comparison can be drawn to the current approach whereby carbon dioxide is released to the atmosphere without engineering controls.

## 3.4 Conclusion

A Carbon Hierarchy is introduced here as an opportunity to re-evaluate the current thought process and policy direction which considers efficiency (avoidance) or capture (sequestration) as meaningful ways to reduce carbon emissions. The newly presented concept of Carbon Stretching provides opportunities to evaluate industrial processes, such as cement manufacturing, in a way that can limit the amount of carbon capture and storage that would be required to achieve carbon neutrality.

The following chapters quantify the various stages of the carbon hierarchy to address the following hypotheses:

Firstly, "*If a successive stage hierarchy for carbon mitigation and material circularity is created it would ensure rational carbon reduction and resource conservation decision making in the cement industry*".

And secondly, "*If such a system can be used to quantify the gap to reach carbon neutrality*".

# Chapter 4

# Analytical Model Development

The following chapter outlines the scope, boundaries, calculations and assumptions of the model design that is used in future chapters as an assessment tool of additive emissions from cement manufacturing. The analytical model development expands on the carbon dioxide emissions associated with manufacturing to quantify the recarbonation of cement. The model evaluates the additive carbon dioxide of end-of-life concrete use in various applications in cement and concrete manufacturing. The outcome is a functional model that will be used to empirically validate the Carbon Hierarchy in future chapters.

## 4.0 Introduction

The following chapter outlines the scope, boundaries, calculations and assumptions of the model that is used in the following chapters as an assessment tool of additive emissions from cement manufacturing. The goal is to assess the optimal use of end-of-life concrete to minimize the carbon dioxide emissions per one tonne of cement.

The focus of this chapter is to establish the model for calculating the carbon dioxide impact associated with material circularity – namely, the use of end-of-life (EOL) concrete into another process either as raw material substitute, a clinker substitute, a cement substitute or an aggregate substitute. Each of these scenarios is explored to understand the potential carbon dioxide uptake and net emissions relative to the individual decisions of where the end-of-life concrete ends up.

Carbon dioxide reduction options, such as Service Life Extension and Process Optimization, not related to carbon uptake are evaluated in Chapter 6. Additionally, Industrial Symbiosis (IS) in the form of mineral component substitution is also evaluated in Chapter 6.

Carbon dioxide uptake by cement is a well-established and researched phenomenon. As presented in Chapter 2, much of the research has focused on a cubic meter of concrete as the functional unit. However, considering that ~90% of carbon dioxide emissions are related to cement manufacturing – a functional unit of kilograms of cement is required as any meaningful carbon dioxide reduction related to concrete manufacturing will require a reduction in cement manufacturing.

This chapter evaluates the specific EOL paths with kilograms of cement as the functional unit.

## 4.1 Carbon Dioxide Uptake Model

In order to establish a model that would be suitable for use with kilograms of cement including carbon dioxide uptake – carbon dioxide uptake per kilograms of concrete is calculated and converted to the desired functional unit. Figure 4.1 shows the key inputs and calculations required to determine the quantity of carbon dioxide uptake by a cubic meter of concrete over a specified period of time.

In much of the research on carbon dioxide uptake, CaO (calcium oxide) in cement is commonly used in recarbonation calculations based on the average jurisdictional information (Kjellsen, Guimaraes, Nilsson, Knut O. Kjellsen, & Nilsson, 2005; Possan, Felix, & Thomaz, 2016). However, this value can be derived from two more precise inputs – namely, *calcination factor* and *% of clinker in Ordinary Portland Cement (OPC) excluding Supplementary Cementitious Materials*. *Concrete thickness (mm)* and *% cement in concrete mix* are expected input variables in the model to allow for accurate calculation of surface area and available cement content.

With these variables and the remaining inputs based on existing research, the flowchart in Figure 4.1 outlines the inputs required (yellow) and the calculations completed (green) to calculate the output of kilograms of $CO_2$ absorbed per cubic meter of concrete over a specified period of time.

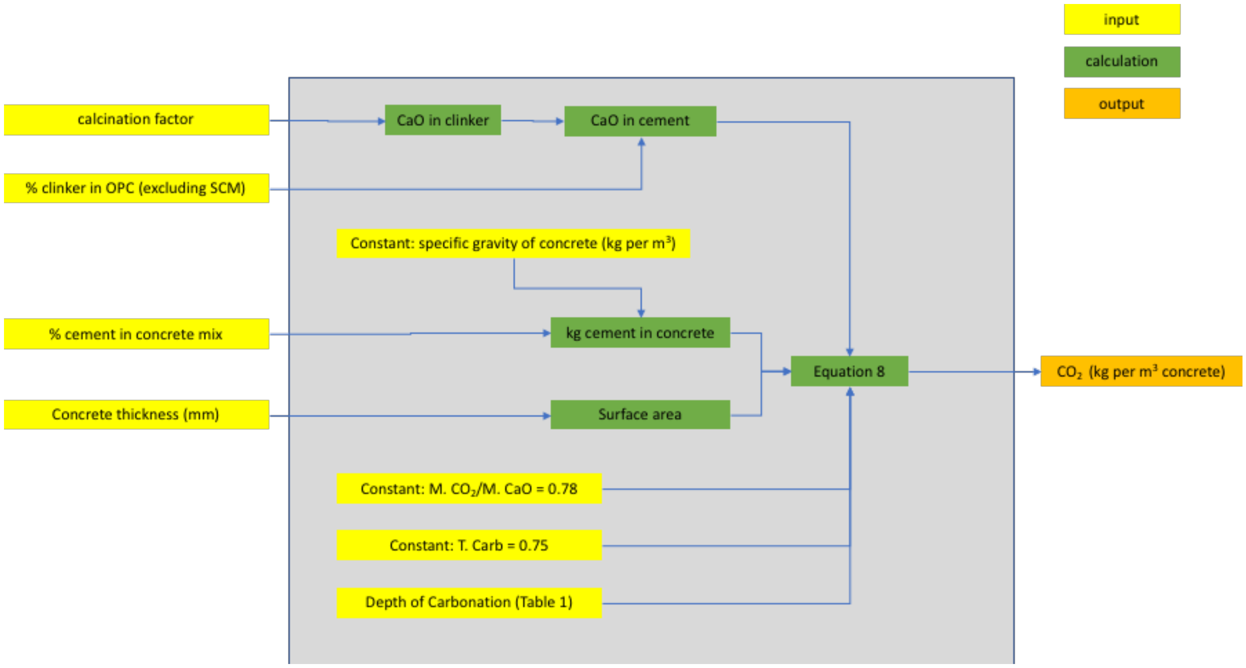


*Figure 4.1: Carbon Uptake Model Input & Output*

***Calcination Factor (kg $CO_2$/t clinker)*** = *Gross $CO_2$ emissions (kg $CO_2$ / t clinker) – [(Thermal energy consumption (MJ / t clinker) * Carbon intensity of the fuel mix (kg $CO_2$ / MJ)] – [(Power consumption up to and including clinker production (kWh / t clinker) * Electrical energy $CO_2$ intensity (kg $CO_2$/kWh)]* ***{Equation 1}***

*Where:*

1. ***Gross $CO_2$ emissions (kg $CO_2$ / t clinker)*** *– WBCSD[1]: 59cAG - Gross $CO_2$ emissions - Weighted average | excluding $CO_2$ from on-site power generation - Grey clinker (kg $CO_2$ / t clinker)*
2. ***Thermal energy consumption (MJ / t clinker)*** *– WBCSD: 93AG - Thermal energy consumption - Weighted average | including drying of fuels - Grey clinker (MJ / t clinker)*
3. ***Carbon intensity of the fuel mix ($CO_2$ / MJ)*** *– WBCSD: 593AG - Carbon intensity of the fuel mix - Weighted average | Grey clinker (g CO2 / MJ) / 1000*
4. ***Power consumption up to and including clinker production (kWh / t clinker)*** *– WBCSD*: 33eAGW - Power consumption up to and including clinker production - Weighted average | Grey and white clinker (kWh / t clinker)*
5. ***Electrical energy $CO_2$ intensity (kg $CO_2$/kWh)*** *- Obtained from jurisdiction specific sources (government publication or electricity distributors)* (Climate Transparency, 2017)

[1] *Several equations throughout this chapter use the World Business Council for Sustainable Development (WBCSD) database survey* (WBCSD, 2015). *The rationale for this is the high level of participation in this form of data collection – specifically for developed nations (2015 cement producer coverage: Europe 93%; North America 80%; South America 59%) and the commonality of variables allowing for repeatability at both the jurisdiction and site level. Further to this, the availability of reported data allows for jurisdictional comparison of best practices by using the specific variable identifiers included for the corresponding variables (in Equation 1: 59cAG, 93AG, 593AG, and 33eAGW).*

The calcination factor can be obtained from the World Business Council for Sustainable Development Cement Protocol (WBCSD) and determined following **Equation 1**. However, a site-specific calcination factor can be used or the calcium oxide (CaO) percentage in clinker can be used as a direct input. Where accurate data is available from the WBCSD or other reporting sources – the calcination factor is used as a primary input in **Equation 2**. The calcination factor represents the $CO_2$ emissions resulting from the decarbonation of calcium carbonate ($CaCO_3$).

Grey cement, or Ordinary Portland Cement (OPC), exclusive of white cement information for some input is not always available. Instead, total cement information is available which includes white cement. Grey cement represents approximately 98% of overall cement production globally (WBCSD, 2015) - as such, the combined value for grey and white cement can be used if more accurate data is not available. This is not of concern for site specific calculations where production or product specific information is available. The expected value for calcination can vary widely but in modern cement plants is near the IPCC default value of 525 kg $CO_2$ per tonne of clinker (WBCSD, 2011).

$$\boldsymbol{CaO\ in\ clinker}\ (\%) = \left(\frac{Calcination\ Factor}{1.03*1000}\right) * \frac{M.\ CaO}{M.\ CO_2} \quad \textit{\{Equation 2\}}$$

*Where:*

1. ***Calcination factor*** *is the value obtained from [Eq. 1]*
2. ***1.03*** *is used to adjust pure CaO and $CO_2$ dissociation (calcination factor of 510 kg $CO_2$/tonne of clinker to the IPCC value of 525 kg $CO_2$/tonne of clinker) to account for TOC, non-CaO carbonated and ABD/CKD production (further explained in Section 4.7.2)*
3. ***1000*** *represented the conversion from kg/t to kg/kg in order to achieve a ratio*
4. ***M. CaO*** *is the molecular weight of calcium oxide (specifically 56.08 g/mol)*
5. ***M. $CO_2$*** *is the molecular weight of carbon dioxide (specifically 44.01 g/mol)*

If CaO in clinker is directly available at a site-specific level, this value can be used to bypass Equations 1 and 2 for use in the model. CaO in clinker will vary depending on jurisdiction but should be approximately 65% for Ordinary Portland Cement OPC (WBCSD, 2011). This value is quite variable in publications (Lee, Park, & Lee, 2013) which may be reflective of whether CaO % in cement is representative of CaO percentage in clinker or cement. The distinction would lead to significant variability as clinker factor decreases[2]. CaO % in cement could be a reflection of CaO % in OPC before Supplementary Cementitious Materials (SCM) are added or afterwards. As such, the most accurate approach (as used in the model) is to utilize CaO % in clinker and calculate the CaO % in cement such that any mineral additives are considered in the making of cement rather than displacement of cement

***CaO in cement*** **=** *CaO in clinker * % clinker in OPC* ***{Equation 3}***

*Where:*

[2] Clinker factor represents the percentage of clinker in cement. Clinker factor decreases when other materials such as blast furnace slag, fly ash, or limestone are ground with clinker to produce various cement types.

***% clinker in OPC*** *= 100 - ΣMineral additives to produce Portland Cement*
*Where:*

1. ***CaO in clinker*** *[Equation 2]*
2. ***Mineral additives to produce Portland Cement*** *- WBCSD: 12AG - Mineral components used to produce Portland cement - Weighted average | Grey cement (% volume of cements)*

Equation 3 or *% clinker in OPC* can be substituted with the site-specific values if available. However, it is important to note that this value is specific to cement not cementitious material which would include mineral additives that displace cement.

***Cement in Concrete (kg/m³)*** *= % cement in concrete mix * S.G. concrete * 1000* ***{Equation 4}***

Where:

1. ***% cement in concrete mix*** *is the amount of cement in concrete*
2. ***S.G. concrete*** *is the specific gravity of concrete*

The specific gravity is multiplied by 1000 to produce a final result in kg of cement per cubic meter of concrete.

Equation 4 can be substituted with site specific information in kilograms per cubic meter of concrete. Specific gravity of 2.7 of concrete is used in the model as a representative value for concrete (depending on cement content) and the specific gravity of limestone (Derry, Michner, Booth, Wahl, & Ontario Geological Survey, 1989) in order to facilitate comparison of end-of-life concrete to raw material input.

***Surface Area for slab (m²)*** = $((1/concrete\ thickness) * 2) + \sqrt{(1/concrete\ thickness) * concrete\ thickness * 4)}$ ***{Equation 5}***

Equation 5 determines the surface area for one cubic meter of concrete for a slab. A slab, or rectangular prism, as the most common shape expected from ready-mix concrete production. Considering the complexity of shapes that concrete may take from precast concrete production, it is too onerous to assess every configuration. However, it can be assumed that most applications will take the shape of a rectangular slab or a series of rectangular slabs as this would represent building walls, road paving, sidewalks, and most infrastructure that is not cylindrical or a unique shape for decorative reasons.

The model output determines the $CO_2$ uptake per cubic meter of concrete. This can be interpreted as the amount of $CO_2$ uptake for the amount of cement used in the concrete and normalized to 1 tonne (1000 kg) of cement as an input into the model for cement manufacturing.

The following formula is a combination of $CO_2$ carbonation models utilized consistently in research (Christian J. Engelsen & Sæther, 2005; Kjellsen et al., 2005; Lagerblad, 2005; Possan et al., 2016; Xi et al., 2016):

$$\boldsymbol{Total\ CO_2\ uptake\ (kg)} = d * c * CaO * T.Carb * S.A. * \frac{M.CO_2}{M.CaO}$$ **{Equation 8}**

*Where;*

***d*** *= depth of carbonation in meters based on Table 4.1 (k value * $\sqrt{year}$)*
***c*** *= cement content in concrete in kilograms per cubic meter [Eq. 4]*
***CaO*** *= percentage of CaO in cement [Eq. 3]*
***T. Carb*** *= percentage total carbonation of CaO [constant]*
***S.A*** *= surface area in square meters [Eq. 5, 6, and 7 or calculated for specific shapes]*
***M.CO2/M.CaO*** *= molecular weight of $CO_2$/molecular weight of CaO [constant]*

| | Compressive Strength of Concrete | | | |
|---|---|---|---|---|
| | <15 MPa | 15-20 MPa | 25-30 MPa | >35 MPa |
| **Wet** | $2\ mm * \sqrt{year}$ | $1.0\ mm * \sqrt{year}$ | $0.75\ mm * \sqrt{year}$ | $0.5\ mm * \sqrt{year}$ |
| **Buried** | $3\ mm * \sqrt{year}$ | $1.5\ mm * \sqrt{year}$ | $1.0\ mm * \sqrt{year}$ | $0.75\ mm * \sqrt{year}$ |
| **Exposed** | $5\ mm * \sqrt{year}$ | $2.5\ mm * \sqrt{year}$ | $1.5\ mm * \sqrt{year}$ | $1\ mm * \sqrt{year}$ |
| **Sheltered** | $10\ mm * \sqrt{year}$ | $6\ mm * \sqrt{year}$ | $4\ mm * \sqrt{year}$ | $2.5\ mm * \sqrt{year}$ |
| **Indoors** | $15\ mm * \sqrt{year}$ | $9\ mm * \sqrt{year}$ | $6\ mm * \sqrt{year}$ | $3.5\ mm * \sqrt{year}$ |

*Table 4.1: d values as adopted from Norden (Kjellsen et al., 2005).*

M. $CO_2$/M.CaO is a constant in the model that represents the molecular weight of $CO_2$ (44.01 g/mol) divided by the molecular weight of CaO (55.08 g/mol). As CaO is presented in kilograms, this constant converts the output from kg of CaO to kg of $CO_2$ – the desired output. Without this constant, Equation 8 would output the total kilograms of CaO which reacted rather than the $CO_2$ absorbed.

T. Carb (total carbonation percentage of CaO) is considered a constant within Equation 8 at 75% (Kjellsen et al., 2005). Research has concluded that with sufficient time it can be assumed that all CaO in cement is recarbonated (Kjellsen et al., 2005; Possan et al., 2016). Accordingly, the constant of 0.75 is used in Equation 8 until the full depth is reached at which time the entire volume of the concrete has recarbonated to 75%. Once this level is reached, it is assumed that the CaO will continue to absorb $CO_2$ until 100% of the CaO has reacted. Equation 8 can be adjusted to control the rate of change as well as maximum $CO_2$ uptake as follows:

$CO_2$ uptake (kg) between two time periods:

$$\boldsymbol{CO_2\ uptake\ (kg)} = (d_2 - d_1) * c * CaO * 0.75 * S.A. * \frac{M.CO_2}{M.CaO}$$ ***{Equation 9}***

*Where:*

***$d_1$*** *= depth of carbonation in meters based on Table 4.1 for time period one (in years)*
***$d_2$*** *= depth of carbonation in meters based on Table 4.1 for time period two (in years)*
***c*** *= cement content in concrete in kilograms per cubic meter [Eq. 4]*
***CaO*** *= percentage of CaO in cement [Eq. 3]*
***T. Carb =*** *percentage total carbonation of CaO [set to 0.75]*
***S.A*** *= surface area in square meters*

***M.CO₂/M.CaO*** *= molecular weight of* $CO_2$*/molecular weight of CaO [constant]*

In Equation 9, the rate of $CO_2$ uptake is controlled to 75% carbonation rate of CaO which represents the limit of the rate at which CaO is recarbonated. In Equation 10, however, T. Carb can be adjusted to 1 in order to account for the assumption that all CaO will recarbonate.

$$\boldsymbol{CO_2\ uptake\ (kg)} = (d_2 - d_1) * c * CaO * 1 * S.A.* \frac{M.CO_2}{M.CaO} \ \textbf{\{Equation 10\}}$$

Where:

***d*** *= depth of carbonation in meters based on Table 4.1 (in years)*
***c*** *= cement content in concrete in kilograms per cubic meter [Eq. 4]*
***CaO*** *= percentage of CaO in cement [Eq. 3]*
***T. Carb*** *= percentage total carbonation of CaO [set to 1]*
***S.A*** *= surface area in square meters [Eq. 5, 6, and 7 or calculated for specific shapes]*
***M.CO2/M.CaO*** *= molecular weight of CO2/molecular weight of CaO [constant]*

Equation 10 is used to calculate the limit of recarbonation for a sample scenario with:

c = 300 kg cement per cubic meter of concrete
CaO = 0.65 (65% CaO in cement)
T. Carb = set to 1 to calculate absolute maximum $CO_2$ uptake by CaO

Maximum recarbonation can be calculated based on the cement content (in kg) regardless of surface area according to Equation 11.

$$\boldsymbol{CO_2\ uptake\ (max\ kg)} = c * CaO * T.Carb * \frac{M.CO_2}{M.CaO} \ \textbf{\{Equation 11\}}$$

= 300 kg * 0.65 * 1 * 0.785
= 153.1 kg

**4.2 Upper Boundaries of Carbon Dioxide Uptake**

In the following section, several ranges of concrete thickness are evaluated to demonstrate how model limits are established based both on rate of carbon dioxide uptake and maximum recarbonation potential of the concrete.

Equation 11 shows that the upper uptake limit for one cubic meter of concrete containing 300 kilograms of cement with a CaO content of 65% is 153.1 kg $CO_2$.

$$\boldsymbol{CO_2\ uptake\ (max\ kg)} = c * CaO * T.Carb * \frac{M.CO_2}{M.CaO}$$

= 300 kg * 0.65 * 1 * 0.785
= 153.1 kg

If T. Carb is set to 0.75, then the maximum uptake would be:

$$\boldsymbol{CO_2\ uptake\ (max\ kg)} = c * CaO * 0.75 * \frac{M.CO_2}{M.CaO}\ \{Equation\ 12\}$$
$$= 300\ \text{kg} * 0.65 * 0.75 * 0.785$$
$$= 114.8\ \text{kg}$$

In the following tests, thickness is set to represent a condition where 1 year into the concrete life the full depth of the concrete would be penetrated, and as such, the maximum recarbonation should be reached. In this example, it is demonstrated how upper boundaries are respected in the model using Equation 8 and 10.

Although penetration occurs from all sides of the material, for consistency with existing calculations. The concrete slab is considered to have only top and bottom penetration to demonstrate the calculations as shown in Figure 4.2A.

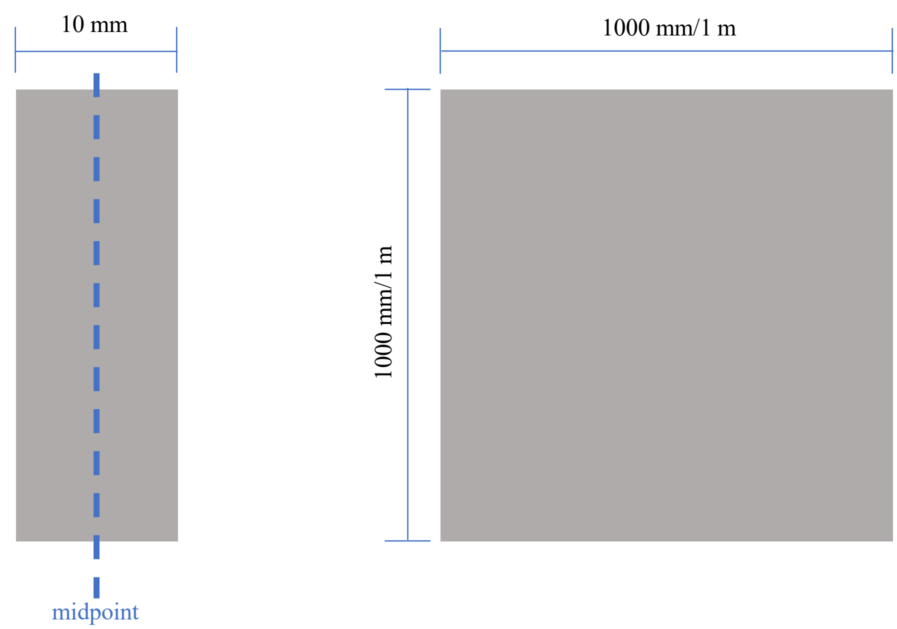


*Figure 4.2A: 10 mm thickness concrete block*

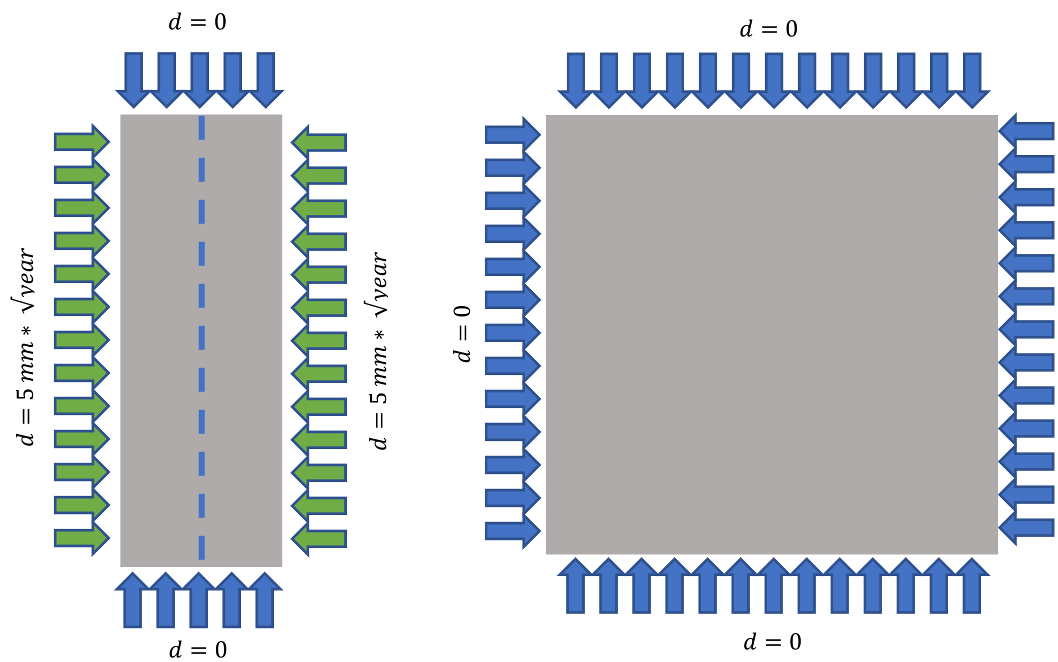


*Figure 4.2B: 10 mm thickness concrete block (only 1 m x 1 m sides considered for calculations); areas affected by green arrows included, areas affected by blue areas excluded. Based on penetration of* $5\,mm * \sqrt{year}$ *from two sides,* $CO_2$ *would penetrate the entire volume of the slab in one year. In reality, if all six sides are included – the full volume penetration would be less than one year (explained further in Section 4.3)*

The maximum $CO_2$ uptake in one year for Exposed Concrete, <15 MPa, 10 mm thickness as presented in Equation 13 below should equal the maximum $CO_2$ uptake as presented in Equation 12, which it does. However, it is assumed that the CaO will continue to react at the same rate until the remain 25% that is unreacted recarbonates. Table 4.2 shows cumulative $CO_2$ uptake per month for this scenario. The results show that after 12 months the full depth (d) of 5 mm (0.005 m) is reached. This is where $CO_2$ has penetrated the slab from the two sides being evaluated and has reached the midpoint, ie. the full volume of concrete is penetrated. From month 13 onwards, depth (d) is a proxy for the amount of CaO reacting from 75% reacted to 100% reacted rather than a true representation as depth cannot exceed 5 mm from each side. From month 13 to 20, T. Carb is maintained at 0.75 to represent the $CO_2$ uptake from 75% to 100% until month 21 when carbonation exceeds the upper boundary of $CO_2$ uptake. At some point between month 20 and 21 all available CaO has reacted with $CO_2$ and the upper boundary of 153.1 kg $CO_2$ has been reached (maximum model boundary as per Equation 11). Figure 3 shows the values of an unconstrained versus constrained model in which the rate of absorption is identical until the maximum boundary of 153.1 kg $CO_2$ is reached.

$$\boldsymbol{CO_2\ uptake\ (kg)} = (d_2 - d_1) * c * CaO * \ T.Carb * S.A. * \frac{M.CO_2}{M.CaO} \ \textbf{\textit{\{Equation 13\}}}$$

$$= \frac{5\,mm * \sqrt{1}}{1000\,mm \div 1\,m} * 300\,kg * 0.65 * 0.75 * \left[\left(\left(\frac{1\,m^3}{0.01\,m}\right) * 2\right) + \left(\sqrt{\frac{1\,m^3}{0.01\,m}}\right) * 0.01 * 4\right)\right] * 0.785$$

= 0.005 * 300 * 0.65 * 0.75 * (200 + 0.4)*0.785

= 0.005 * 300 * 0.65 * 0.75 * 200 * 0.785

= 114.8 kg

*Note: 0.4 m² associated with edges of slab are eliminated for the purposes of this example to calculate the penetration of $CO_2$ from the larger flat sides of the slab and not the surrounding four edges (highlighted in red above).*

| Model Inputs | | | | | | | | Model Outputs | |
|---|---|---|---|---|---|---|---|---|---|
| d | c | CaO | T. Carb | S.A. | M | Years | *Months* | $CO_2$ Uptake (without upper constraint) | $CO_2$ uptake (with upper constraint) |
| 0.00144338 | 300 | 0.65 | 0.75 | 200 | 0.785 | 0.08333333 | *1* | 33.1 | 33.1 |
| 0.00204124 | 300 | 0.65 | 0.75 | 200 | 0.785 | 0.16666667 | *2* | 46.9 | 46.9 |
| 0.0025 | 300 | 0.65 | 0.75 | 200 | 0.785 | 0.25 | *3* | 57.4 | 57.4 |
| 0.00288675 | 300 | 0.65 | 0.75 | 200 | 0.785 | 0.33333333 | *4* | 66.3 | 66.3 |
| 0.00322749 | 300 | 0.65 | 0.75 | 200 | 0.785 | 0.41666667 | *5* | 74.1 | 74.1 |
| 0.00353553 | 300 | 0.65 | 0.75 | 200 | 0.785 | 0.5 | *6* | 81.2 | 81.2 |
| 0.00381881 | 300 | 0.65 | 0.75 | 200 | 0.785 | 0.58333333 | *7* | 87.7 | 87.7 |
| 0.00408248 | 300 | 0.65 | 0.75 | 200 | 0.785 | 0.66666667 | *8* | 93.7 | 93.7 |
| 0.00433013 | 300 | 0.65 | 0.75 | 200 | 0.785 | 0.75 | *9* | 99.4 | 99.4 |
| 0.00456435 | 300 | 0.65 | 0.75 | 200 | 0.785 | 0.83333333 | *10* | 104.8 | 104.8 |
| 0.00478714 | 300 | 0.65 | 0.75 | 200 | 0.785 | 0.91666667 | *11* | 109.9 | 109.9 |
| 0.005 | 300 | 0.65 | 0.75 | 200 | 0.785 | 1 | *12* | 114.8 | 114.8 |
| 0.00520416 | 300 | 0.65 | 0.75 | 200 | 0.785 | 1.08333333 | *13* | 119.5 | 119.5 |
| 0.00540062 | 300 | 0.65 | 0.75 | 200 | 0.785 | 1.16666667 | *14* | 124 | 124 |
| 0.00559017 | 300 | 0.65 | 0.75 | 200 | 0.785 | 1.25 | *15* | 128.4 | 128.4 |
| 0.0057735 | 300 | 0.65 | 0.75 | 200 | 0.785 | 1.33333333 | *16* | 132.6 | 132.6 |
| 0.00595119 | 300 | 0.65 | 0.75 | 200 | 0.785 | 1.41666667 | *17* | 136.6 | 136.6 |
| 0.00612372 | 300 | 0.65 | 0.75 | 200 | 0.785 | 1.5 | *18* | 140.6 | 140.6 |
| 0.00629153 | 300 | 0.65 | 0.75 | 200 | 0.785 | 1.58333333 | *19* | 144.5 | 144.5 |
| 0.00645497 | 300 | 0.65 | 0.75 | 200 | 0.785 | 1.66666667 | *20* | 148.2 | 148.2 |
| 0.00661438 | 300 | 0.65 | 0.75 | 200 | 0.785 | 1.75 | *21* | 151.9 | **151.3** |
| 0.00677003 | 300 | 0.65 | 0.75 | 200 | 0.785 | 1.83333333 | *22* | 155.4 | **151.3** |
| 0.00692219 | 300 | 0.65 | 0.75 | 200 | 0.785 | 1.91666667 | *23* | 158.9 | **151.3** |
| 0.00707107 | 300 | 0.65 | 0.75 | 200 | 0.785 | 2 | *24* | 162.4 | **151.3** |

*Table 4.2: Uptake Upper Constraints (example)*

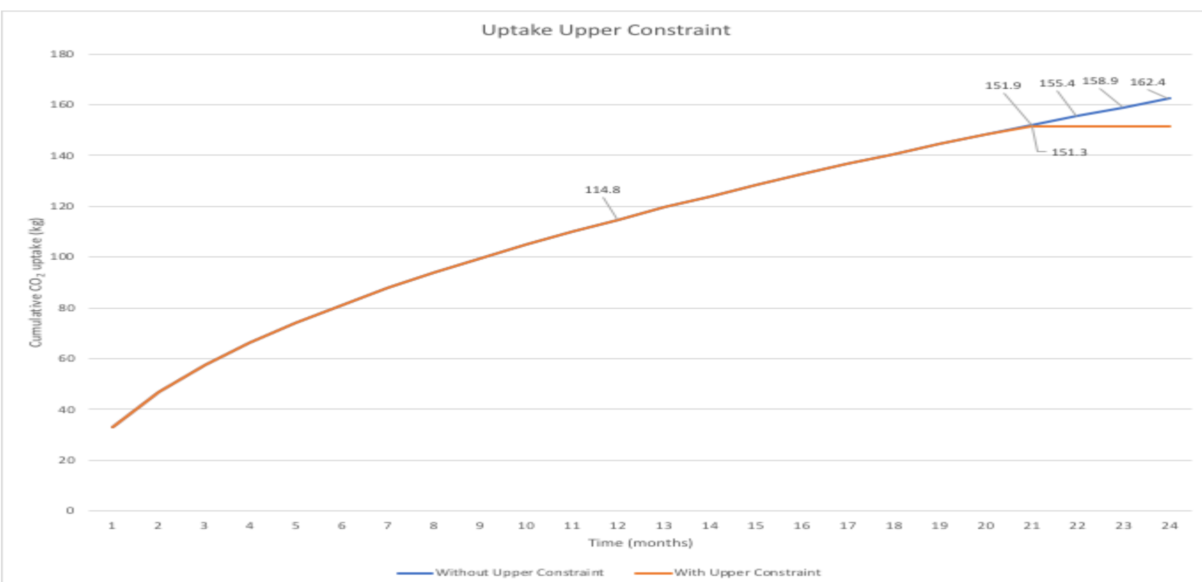


*Figure 4.3: Uptake Upper Constraint (example)*

It is important to reinforce that the constant T is 0.75 to reflect the $CO_2$ uptake rate as established in previous research (Kjellsen et al., 2005; Lagerblad, 2005). The assumption that the calculation with T = 0.75 is also the upper constraint may be limiting, as research has shown that carbonation can exceed 75% and, in fact, can reach 100%. The distinction is between rate and upper constraint - the calculation for rate should be set to T = 0.75 while the maximum potential $CO_2$ uptake can be calculated under the conservative assumption with T = 0.75 or alternatively, assuming that T = 1. The model is structured such that this value can be adjusted to validate the difference in $CO_2$ uptake potential.

### 4.3 Boundaries/Error Correction for Surface Area Overlap

It is important to note that in all scenarios calculated within the model, d (depth) should not be considered as the exact depth of carbonation but rather a proxy to calculate the total $CO_2$ uptake. This is unavoidable as in all scenarios and concrete shapes all sides are exposed to some environment (either wet, buried, exposed, sheltered, or indoors). When the full surface area is considered the corners (in the example of a slab presented in Figure 4) would experience overlapping penetration as shown below.

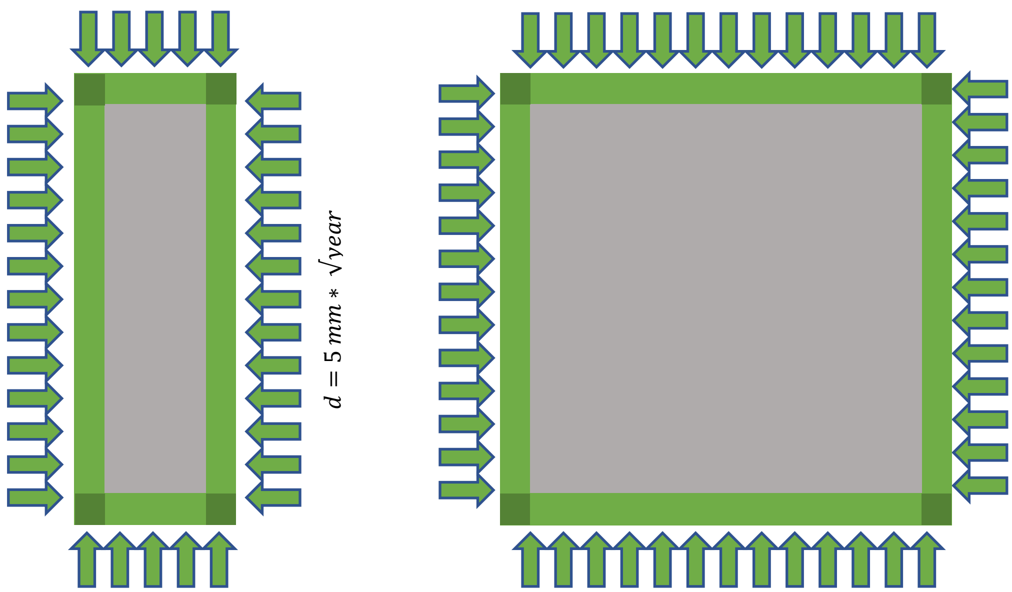


*Figure 4.4: slab penetration - as evaluated in Figure 4.3 would, in reality, have penetration from all sides and some overlap at the corners.*

In order to account for the potential discrepancy between penetration depth as an accurate value of depth rather than a proxy for depth, the model considers error calculations for the potential of double counting at the corners as shown in Figure 4. Equation 5 is adjusted to eliminate the potential double counting as follows:

***Adjusted surface area for slab (m²)*** = $((1/concrete\ thickness) * 2) + \sqrt{(1/concrete\ thickness)} * concrete\ thickness * 4) - [\sqrt{(1/concrete\ thickness)} * d * 8)]$ ***{Equation 14}***

Equation 14 assumes that the slab length and width are equal. For the purposes of adjusting surface area to account for potential double counting, Equation 14 does not need to be adjusted for unequal length and width as the sum of the surface area will be the same as long as depth is consistent.

Equation 14 is used to calculate an adjusted surface area to remove overlapping penetration. The output (in kilograms of $CO_2$ per cubic meter of concrete) is compared for the unadjusted surface area as presented in Equation 5 and the adjusted surface area as presented in Equation 14. All output tables are included in Appendix A with Tables 4.3 and 4.4 highlighting the potential maximum error for 100-year and 500-year exposure, respectively. Slab thickness of 10 mm through 1000 mm are calculated to evaluate the potential error associated with overlapping penetration area. As expected, the error increases with time as additional surface area on the corners overlaps. For all d values as presented in Table 4.3, the maximum error for 100-year exposure is 1.68 % per millimeter. For all d < 9 mm * $\sqrt{year}$ the maximum error for 500-year exposure is 3.76 % per millimeter. For all d > 9 mm * $\sqrt{year}$ which includes three scenarios (Sheltered < 15 MPa; Indoor < 15 MPa; Indoor 15-20 MPa) the maximum errors for 500-year exposure are 3.74, 3.74, and 3.45 per millimeter, respectively.

| | Compressive Strength of Concrete | | | |
|---|---|---|---|---|
| | <15 MPa | 15-20 MPa | 25-30 MPa | >35 MPa |
| **Wet** | **3.36%** | **1.68%** | **1.26%** | **0.84%** |
| **Buried** | **5.04%** | **2.52%** | **1.68%** | **1.26%** |
| **Exposed** | **8.40%** | **4.20%** | **2.52%** | **1.68%** |
| **Sheltered** | **16.8%** | **10.1%** | **6.7%** | **4.2%** |
| **Indoors** | **25.2%** | **15.1%** | **10.1%** | **5.9%** |

***Table 4.3:*** *100-year exposure scenario maximum surface area error. Maximum error – 1.68 % per mm as presented in Table 4.3. For example, Wet < 15 MPa, d = 2 mm ** $\sqrt{year}$*, therefore, maximum error in 100 years is 3.36 %.*

| | Compressive Strength of Concrete | | | |
|---|---|---|---|---|
| | <15 MPa | 15-20 MPa | 25-30 MPa | >35 MPa |
| **Wet** | **7.52%** | **3.76%** | **2.82%** | **1.88%** |
| **Buried** | **11.3%** | **5.64%** | **3.76%** | **2.82%** |
| **Exposed** | **18.8%** | **9.40%** | **5.64%** | **3.76%** |
| **Sheltered** | **37.4%** | **22.6%** | **15.0%** | **9.40%** |
| **Indoors** | **51.8%** | **33.7%** | **22.6%** | **13.2%** |

***Table 4.4:*** *500-year exposure scenario maximum surface area error. Maximum error – 3.76 % per mm as presented in Table 4.3 with exception of: Sheltered < 15 MPa; Indoor < 15 MPa; and Indoor 15-20 MPa . For example, Wet < 15 MPa, d = 2 mm ** $\sqrt{year}$*, therefore, maximum error in 500 years is 7.52 %. Error for Sheltered < 15 MPa = 3.74 % per mm, Indoor < 15 MPa = 3.74 % per mm, and Indoor 15-20 MPa = 3.45 % per mm.*

It is important to note that current literature does not discuss this potential error. Therefore, it is not clear whether the error exists and is simply overlooked in the literature or whether the equation is already adjusted to correct for such overlap. Considering this limitation, these values are used for sensitivity analysis to account for potential overestimation of $CO_2$ uptake in the results.

### 4.4 Full Carbonation Evaluation in Years

In order to move to the next stage of the model it is critical to understand the maximum years required to reach full carbonation. This value is important as the availability of unreacted cement (as will be shown in the results) plays a significant role in the reduction of carbon dioxide emissions from a lifecycle standpoint for cement that is reintroduced into the kiln or cement mills. If the CaO is fully recarbonated then the concrete being used for cement manufacturing can be considered the equivalent to raw material input with respect to carbon dioxide.

In order to calculate years of exposure required to reach complete recarbonation, Equation 8 is rearranged as shown in Equation 15.

$$\boldsymbol{CO_2\ uptake\ (max\ kg)} = d * c * CaO * T.Carb * S.A * \frac{M.CO_2}{M.CaO}$$

$$\boldsymbol{CO_2\ uptake\ (max\ kg)} = d\ factor\ (mm\ from\ Table\ 3) * \sqrt{year} * c * CaO * T.Carb * S.A * \frac{M.CO_2}{M.CaO} \quad \textbf{\{Equation 15\}}$$

$$\sqrt{year} = \frac{Total\ CO_2\ uptake}{d\ factor * c * T.Carb * S.A. * \frac{M.CO2}{M.CaO}}$$

$$\boldsymbol{year} = \left(\frac{Total\ CO2\ uptake}{d\ factor * c * T.Carb * S.A. * \frac{M.CO2}{M.CaO}}\right)^2 \quad \textbf{\{Equation 16\}}$$

Since, $\boldsymbol{CO_2\ uptake\ (max\ kg)} = c * CaO * T.Carb * \frac{M.CO_2}{M.CaO}$ (as per Equation 12), Equation 16 can be rewritten as:

$$\boldsymbol{year} = \left(\frac{1}{d\ factor * S.A.}\right)^2 \quad \textbf{\{Equation 17\}}$$

Equation 17 is used to calculate the values in Table 4.5 while Equation 18 is used to calculate the values in Table 4.6 accounting for overlapping penetration error as presented in Table 4.3.

$$\boldsymbol{year} = \left(\frac{1}{d\ factor * [S.A. * \left(1 - d\ factor * \frac{1.68}{100}\right)]}\right)^2 \quad \textbf{\{Equation 18\}}$$ [3]

[3] It should be noted that Equation 18 applies for 100-year evaluation based on the error correction of 1.68% that is used in the calculation. The equation is modified for the appropriate error as per Tables 4.3 and 4.4 for 500-year time period.

| Concrete Strength | Type of Exposure | k value | Depth (mm) 10 | 20 | 30 | 40 | 50 | 100 | 150 | 200 | 250 | 300 | 350 | 400 | 450 | 500 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Indoor | <15 MPa | 15 | 0.1 | 0.4 | 1.0 | 1.7 | 2.7 | 9.8 | 20.1 | 32.0 | 44.4 | 56.6 | 68.1 | 78.4 | 87.5 | 95.3 |
| Sheltered | <15 MPa | 10 | 0.2 | 1.0 | 2.2 | 3.9 | 6.0 | 22.1 | 45.1 | 72.0 | 100.0 | >100 | >100 | >100 | >100 | >100 |
| Indoor | 15-20 MPa | 9 | 0.3 | 1.2 | 2.7 | 4.8 | 7.4 | 27.3 | 55.7 | 88.8 | >100 | >100 | >100 | >100 | >100 | >100 |
| Sheltered | 15-20 MPa | 6 | 0.7 | 2.7 | 6.1 | 10.8 | 16.6 | 61.4 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| Indoor | 25-30 MPa | 6 | 0.7 | 2.7 | 6.1 | 10.8 | 16.6 | 61.4 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| Exposed | <15 MPa | 5 | 1.0 | 4.0 | 8.8 | 15.5 | 23.9 | 88.5 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| Sheltered | 25-30 MPa | 4 | 1.6 | 6.2 | 13.8 | 24.2 | 37.4 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| Indoor | >35 MPa | 3.5 | 2.0 | 8.1 | 18.0 | 31.6 | 48.8 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| Buried | <15 MPa | 3 | 2.8 | 11.0 | 24.5 | 43.1 | 66.4 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| Exposed | 15-20 MPa | 2.5 | 4.0 | 15.8 | 35.3 | 62.0 | 95.7 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| Sheltered | >35 MPa | 2.5 | 4.0 | 15.8 | 35.3 | 62.0 | 95.7 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| Wet | <15 MPa | 2 | 6.2 | 24.7 | 55.1 | 96.9 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| Buried | 15-20 MPa | 1.5 | 11.1 | 43.9 | 98.0 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| Exposed | 25-30 MPa | 1.5 | 11.1 | 43.9 | 98.0 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| Wet | 15-20 MPa | 1 | 24.9 | 98.9 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| Buried | 25-30 MPa | 1 | 24.9 | 98.9 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| Exposed | >35 MPa | 1 | 24.9 | 98.9 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| Wet | 25-30 MPa | 0.75 | 44.3 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| Buried | >35 MPa | 0.75 | 44.3 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| Wet | >35 MPa | 0.5 | 99.6 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |

*Table 4.5: Number of years to reach full recarbonation of 1 m³ of concrete – as per Equation 18. Full table available in Appendix B.*

| Concrete Strength | Type of Exposure | k value | Depth (mm) 10 | 20 | 30 | 40 | 50 | 100 | 150 | 200 | 250 | 300 | 350 | 400 | 450 | 500 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Indoor | <15 MPa | 15 | 0.2 | 0.8 | 1.8 | 3.1 | 4.7 | 17.6 | 35.9 | 57.2 | 79.4 | >100 | >100 | >100 | >100 | >100 |
| Sheltered | <15 MPa | 10 | 0.4 | 1.4 | 3.2 | 5.6 | 8.6 | 31.9 | 65.2 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| Indoor | 15-20 MPa | 9 | 0.4 | 1.7 | 3.8 | 6.6 | 10.2 | 37.9 | 77.4 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| Sheltered | 15-20 MPa | 6 | 0.9 | 3.4 | 7.6 | 13.3 | 20.5 | 76.0 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| Indoor | 25-30 MPa | 6 | 0.9 | 3.4 | 7.6 | 13.3 | 20.5 | 76.0 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| Exposed | <15 MPa | 5 | 1.2 | 4.7 | 10.5 | 18.5 | 28.5 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| Sheltered | 25-30 MPa | 4 | 1.8 | 7.1 | 15.8 | 27.8 | 43.0 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| Indoor | >35 MPa | 3.5 | 2.3 | 9.1 | 20.3 | 35.7 | 55.1 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| Buried | <15 MPa | 3 | 3.1 | 12.2 | 27.2 | 47.7 | 73.7 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| Exposed | 15-20 MPa | 2.5 | 4.3 | 17.2 | 38.4 | 67.6 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| Sheltered | >35 MPa | 2.5 | 4.3 | 17.2 | 38.4 | 67.6 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| Wet | <15 MPa | 2 | 6.7 | 26.5 | 59.0 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| Buried | 15-20 MPa | 1.5 | 11.6 | 46.2 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| Exposed | 25-30 MPa | 1.5 | 11.6 | 46.2 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| Wet | 15-20 MPa | 1 | 25.8 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| Buried | 25-30 MPa | 1 | 25.8 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| Exposed | >35 MPa | 1 | 25.8 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| Wet | 25-30 MPa | 0.75 | 45.4 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| Buried | >35 MPa | 0.75 | 45.4 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |
| Wet | >35 MPa | 0.5 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 | >100 |

*Table 4.6: Number of years to reach full recarbonation of 1 m³ of concrete accounting for overlapping penetration – as per Equation 19. Full table available in Appendix B.*

Tables 4.5 and 4.6 highlight that with both types of evaluation, namely with and without overlapping penetration, nearly all 10 mm depth slabs would experience full penetration. The only exception for 10 mm full recarbonation would be Wet, > 35 MPa which would require 101.3 years to reach full recarbonation if overlapping is considered (99.6 years without consideration for overlapping penetration). However, for slabs that are 100 mm or greater in depth, there are fewer and fewer scenarios under which full recarbonation is reached within 100 years as shown in Table 4.5 and 4.6 – regardless of whether overlapping penetration is considered or not. Therefore, evaluation for different end-of-life uses of concrete is justified with specific focus on the $CO_2$ benefit of unreacted cement. Further evaluation would not be justified if concrete would have been expected to be fully recarbonated, meaning that no unreacted cement would be available.

## 4.5 Purpose of the Evaluation

As stated in the Section 4.3, the evaluation for different end-of-life uses of concrete shows that full recarbonation of cement does not occur for most scenarios above 100 mm in depth which represents most residential, commercial, and infrastructure applications of concrete (ie. 100

mm/~4 inches or greater). This justifies continuing the evaluation of various pathways for EOL concrete whereas complete recarbonation would not due to the fact that completely recarbonated material would not offer any benefit for reduced operational emissions or carbon dioxide uptake during secondary use.

The model aims to determine the best application of end-of-life concrete with respect to total $CO_2$ emissions from a lifecycle perspective with kg $CO_2$ per tonne of cement as the key performance indicator. Current research has focused on the use of end-of-life concrete as an aggregate or use of techniques to increase the rate of $CO_2$ uptake. Although this is a valid approach, it does not consider the value of unreacted cement as a product but simply as a carbon sink for sequestration. The goal of this research is to understand the potential to reduce $CO_2$ impact over the entire cement manufacturing process rather than accelerate the rate of $CO_2$ uptake. As shown in Sections 4.1-4.4, $CO_2$ uptake can be expected to occur regardless of application of cement with the distinguishing factor being the rate of that uptake.

The following applications are considered in evaluating the total $CO_2$ impact of cement manufacturing (in all scenarios, values are normalized to reflect additive impacts of producing one tonne of cement – "additive $CO_2$ per tonne of cement" is explained in detail in Section 4.7.1):

1. Baseline Scenario – this is the traditional approach of evaluating the impact of production with the consideration of carbon uptake during the useful life of concrete. The consideration of carbon uptake in a lifecycle assessment is unique in concrete due to the availability of CaO in cement (Kjellsen et al., 2005; Possan et al., 2016; Xi et al., 2016).
2. Raw Material Substitution – this is a relatively novel approach with some researchers focusing on similar evaluations (De Schepper, De Buysser, Van Driessche, & De Belie, 2013). It is presented in this research to assess the benefit of end-of-life concrete substituting raw material input in the clinker manufacturing process.
3. Clinker Substitution – this is a novel approach presented in this research to assess the benefit of end-of-life concrete substituting clinker entering the cement mill.
4. Cement Substitution – this approach assesses the benefit of end-of-life concrete substituting cement in concrete (specifically, the portion of unreacted cement substituting cement). However, it will be demonstrated empirically that even in optimal conditions the benefit would be nil resulting in exclusion from the model.
5. Aggregate Substitution – this scenario has been evaluated by numerous researchers as presented in Chapter 2 prior to the work presented here. In this research, the assessment is used as an empirical comparison to cement and clinker substitution.

Model development, limitations and boundaries are detailed for each of the above scenarios in Section 4.7.

### 4.6 Scope of the Assessment

The stages of the cement process included in the assessment are raw material extraction, manufacturing, recarbonation during use, and end-of-life. The assessment compares a baseline scenario of raw material extraction and manufacturing (in addition to recarbonation during use) to EOL concrete pathways of Raw Material, Clinker, and Aggregate Substitution.

Similar processes that are bound to exist are excluded for consistency and simplicity of the model. For example, raw material quarrying and primary crushing represents less than 2% of electrical energy (Aranda Usón, López-Sabirón, Ferreira, & Llera Sastresa, 2013) the cement manufacturing process (or ~0.4% of the $CO_2$ emissions[4]) and less than 0.5% of the $CO_2$ impact for activities outside electrical energy consumption due to fossil fuel use (Nisbet, Marceau, & Vangeem, 2002). As such, the difference associated with processing end-of-life concrete versus natural raw material would be a portion of less than 1% of the production emissions. Since the differences would be negligible, the assumption is made that the impacts are equivalent. However, the crushing of concrete for EOL use as aggregate is included since this would represent an additional input rather than a substitute.

It should be noted that a comparison of concrete to other building materials is not the purpose of this research. The assessment is internally focused on the cement manufacturing process. The goal of the assessment is to determine whether cement, with its unique recarbonation ability, has the potential to reach carbon neutrality.

Transportation is intentionally excluded from this model. In previous research studies, transportation can have significant impact in assessing $CO_2$ emissions related to EOL concrete application selection (De Schepper, Van den Heede, Van Driessche, & De Belie, 2014; Di Maria, Eyckmans, & Van Acker, 2018; H. S. Lee & Wang, 2016). In turn, the focus of EOL concrete application relied on one factor – distance the EOL concrete needed to be transported for reuse. In these previous assessments, the assumption is that the transportation industry will not change either its mode of energy use (and in turn carbon emissions) or evolve to create efficiencies. This research assumes that the logistics industry is driving towards carbon neutrality itself.

Sensitivity analysis is completed for changes in technology associated with reduced carbon intensity of fuel, carbon intensity of electricity, specific electricity use, and specific fuel use but it is fundamentally accepted (in this research) that the chemical process of disassociating carbon dioxide from calcium carbonate will continue in the manufacturing of cement.

[4] Assuming a worst-case scenario where 20% of the cement manufacturing emissions are from electricity production. This scenario would be a highly inefficient facility with electricity generates primarily by fossil fuels.

### 4.7 Additive Carbon Dioxide Model

#### 4.7.1 Baseline Scenario

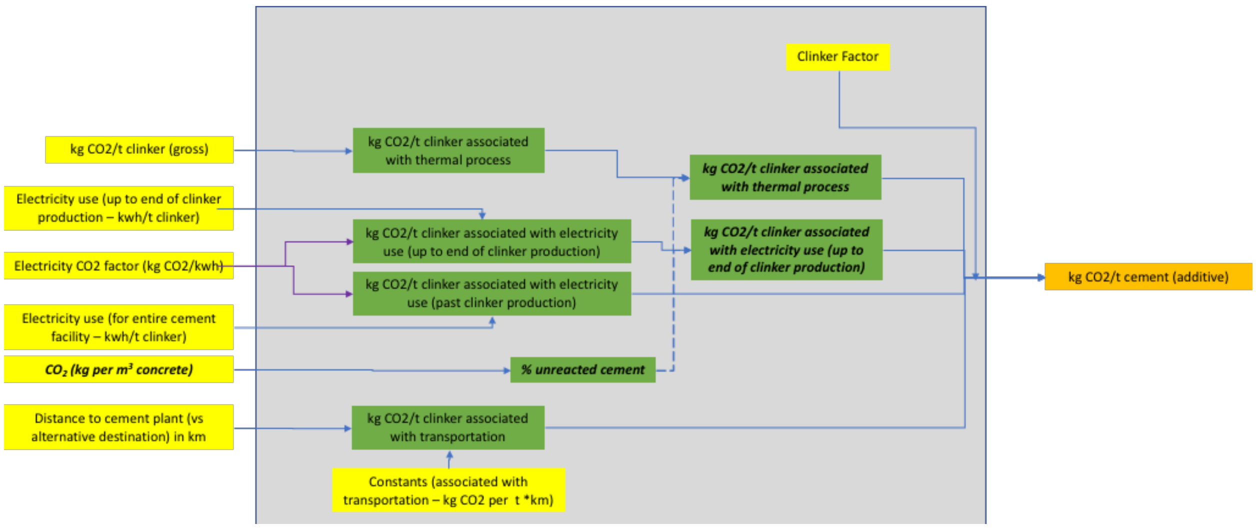


*Figure 4.5: Additive $CO_2$ Model for Raw Material and Clinker Substitution*

Figure 4.5 shows the Additive $CO_2$ model for Raw Material and Clinker Substitution. The additive carbon dioxide model calculates the total carbon dioxide emissions associated with production of one tonne of cement less the carbon uptake associated with the same tonne of cement at a point in time (t) representing the years since the production of the cement (or service life).

The *baseline scenario* represents the condition where concrete is not demolished, crushed, or reused in any way. In other words, the slab of concrete remains in place as it was originally poured or placed. The baseline scenario is calculated using the following equation:

***Additive[5] $CO_2$ (kg/t cement) at time*** = $[(ther.\ process + calc.factor) * \%\ clinker\ in\ OPC] + (Elec.F\ x\ Elec.Facility) - CO_2\ uptake\ (per\ tonne)$ ***{Equation 19}***

*Where:*

1. ***ther. process*** = *kg $CO_2$/t clinker gross which provided the CO2 emissions per tonne of clinker associated with the thermal process and obtained from Gross $CO_2$ emissions (kg $CO_2$ / t clinker) – WBCSD: 59cAG - Gross CO2 emissions - Weighted average | excluding $CO_2$ from on-site power generation - Grey clinker (kg $CO_2$ / t clinker) as a direct input value into the model.*

[5] "additive" rather than "net" is used as "net emissions" has an existing meaning in cement nomenclature referring to benefits associated with use of alternative fuels in cement facilities versus alternative disposal options.

2. ***calc. factor** = calcination factor as calculated in Equation 1*
3. ***% clinker in OPC** = 1 - % Mineral additives to produce Portland Cement - WBCSD: 12AG - Mineral components used to produce Portland cement - Weighted average | Grey cement (% volume of cements)*
4. ***Elec. F** = Electricity $CO_2$ factor (kg $CO_2$/kwh) | Obtained from jurisdictional electricity provider*
5. ***Elec. Facility** = Electricity use (for entire facility – kwh/t clinker) – WBCSD: 33AGW - Cement plant power consumption - Weighted average | Grey and white cement (kWh / t cement)*
6. ***$CO_2$ uptake (per tonne)** is calculated from Equation 10. This value can then be normalized to one tonne of cement with the following equation:*

$$CO_2 \text{ (kg uptake per tonne cement)} = \frac{CO_2 \text{ kg uptake per m3 concrete}}{c/1000} \quad \{\text{Equation 20}\}$$

*Where:*

***$CO_2$ kg per m3 concrete** = result from Equation 10*
***c** = cement content in concrete in kilograms per cubic meter (divided by 1000 to convert kg/t)*

It is important to note that Equation 10 is not converted to kilograms per tonne of cement prior to this point in the model. The conversion would not accurately represent the output from Equation 10 as the rate of $CO_2$ uptake would be overestimated if surface area and cement content were adjusted unless the final output is divided by the total volume of concrete produced. Since the latter approach requires an additional variable, the model is simplified to use $CO_2$ in kilograms per cubic meter of concrete and then normalized to one tonne of cement equivalent.

Equation 19 calculates the additive $CO_2$ emissions associated with the production and uptake of cement representing the baseline scenario. The benefits of unreacted cement are not captured as the concrete is not reused in any way.

This evaluation (unlike the others presented) does not continue past the initial service life of the concrete.

### 4.7.2 Lower Limit for Calcination Emissions

Using Equation 11, a maximum 153.1 kg of $CO_2$ would be captured with 300 kg of cement or 510 kg of $CO_2$ captured per tonne of cement. This value represents the theoretically optimal calcination factor for cement as presented earlier. This does not capture other aspects of the process such as Total Organic Carbon (TOC), non-CaO based carbonates that may be present in the raw material, the production of Cement Kiln Dust (CKD) or Alkali Bypass Dust (ABD). The WBCSD recommends the use of 525 kg $CO_2$/t clinker associated with calcination (WBCSD, 2011). However, for the purpose of the model – a third value, the difference between the total $CO_2$ emissions per tonne of clinker and the $CO_2$ emissions associated with the thermal input, is calculated. This value allows for a jurisdiction or site-specific value to be used that considers $CO_2$ emissions for all potential raw material needs to produce clinker aside from thermal input inclusive of fuel drying.

The following equations are used to ensure the lower limit of calcination is respected:

***$CO_2$ associated with thermal process (kg/t clinker) =*** *average carbon intensity of fuel (kg $CO_2$/MJ) * thermal energy input incl. fuel drying (MJ/t clinker)* ***{Equation 21}***

*Where:*

***Average Carbon Intensity of Fuel (kg CO2 / MJ)*** *– WBCSD: 593AG - Carbon intensity of the fuel mix - Weighted average | Grey clinker (CO2 / MJ)*
***Thermal Energy Input incl. fuel drying (MJ/t clinker)*** *– WBCSD: 93AG - Thermal energy consumption - Weighted average | including drying of fuels - Grey clinker (MJ / t clinker)*

***$CO_2$ associated with calcination (kg/t clinker) =*** *Gross $CO_2$ emissions (per tonne of clinker) – $CO_2$ associated with thermal process (kg/t clinker)* ***{Equation 22}***

*Where;*

***Gross $CO_2$ emissions (kg CO2 / t clinker)*** *= WBCSD: 59cAG - Gross $CO_2$ emissions - Weighted average | excluding CO2 from on-site power generation*
***$CO_2$ associated with thermal process (kg/t clinker) = r****esult from Equation 21*

It should be noted that Equation 21 and 22 simply disaggregate the value associated with the thermal process – therefore, **Gross $CO_2$ emissions (kg $CO_2$/t clinker)** can be used to calculate the same result. However, Equation 22 is important to confirm the model limit and must satisfy the following minimum.

***Lower limit for Equation 22*** = *CaO* * $\frac{M.\ CaO}{M.\ CO_2}$ * *M. CaO/M. CO2 * 1000 {Equation 23}*

*Where:*

***CaO =*** *percentage of CaO in clinker*
***M.CaO*** *= molecular weight of CaO [constant = 56.08]*
***$M.CO_2$ =*** *molecular weight of $CO_2$ [constant = 44.01]*

If the default value of 65% CaO in clinker is used, then Equation 23 would equal 510 kg $CO_2$/t clinker. The value of Equation 22 can be higher representing the TOC or non-CaO based carbonates that may be present in the raw material or the production of CKD and ABD in the clinker manufacturing process. This value may also differ if the CaO in clinker differs for site specific input, however, this lower limit ensures that Equation 11 (maximum $CO_2$ uptake by concrete) does not exceed Equation 22 ($CO_2$ from calcination). This limit ensures that the model does not calculate more $CO_2$ being absorbed by CaO than $CO_2$ released from $CaCO_3$ disassociation (in other words – greater than 100% reabsorption of $CO_2$ by the cement).

### 4.7.3 Raw Material Substitution Scenario

The Raw Material Substitution scenario considers the return of concrete to the beginning of the cement manufacturing process referring specifically to the displacement of quarried raw materials used for raw feed to the kiln.

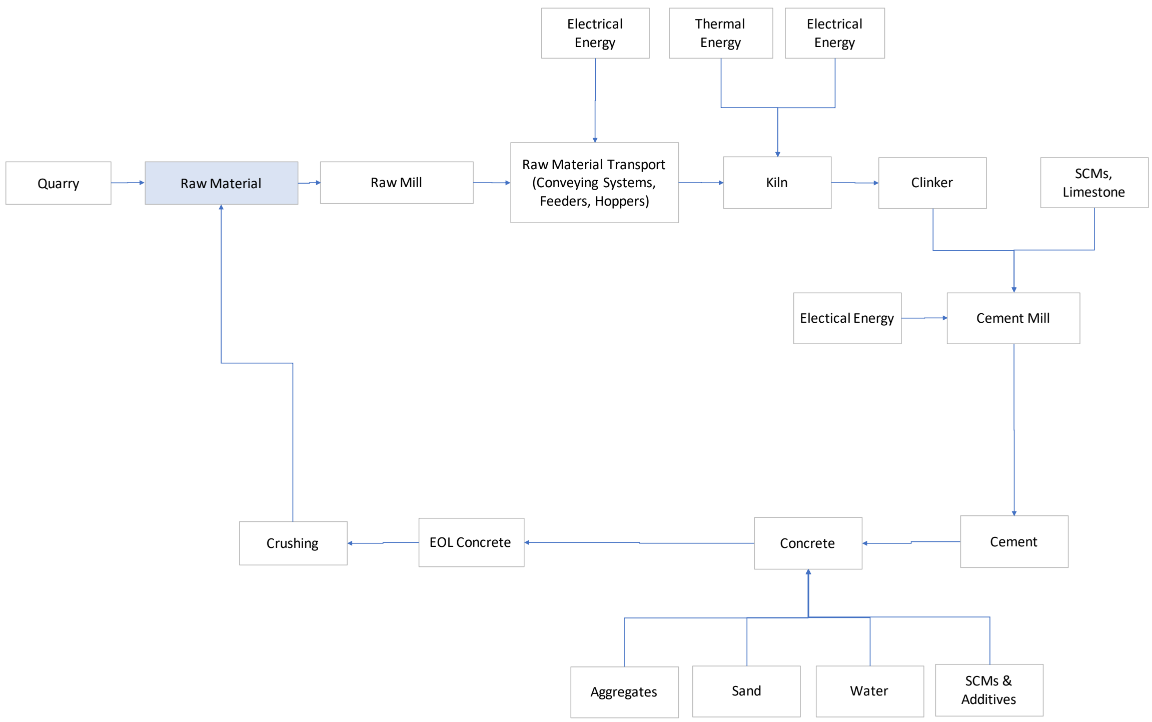


*Figure 4.6: Process Flowchart for Raw Material Substitution*

As shown in Figure 4.6, EOL concrete is returned to the cement manufacturing facility to displace incoming raw material from the quarry. The raw material and crushed concrete are assumed to be chemically and physically identical with the exception of the unreacted cement in the recycled concrete, determined as follows:

$$\textbf{\textit{Unreacted cement}}\ (\%) = \frac{Max\ CO_2\ uptake\ (kg)\ \{Eq.11\} - Total\ CO_2\ uptake\ (kg)\ \{Eq.8\}}{Max\ CO_2\ uptake\ (kg)\ \{Eq.11\}}\ \{Equation\ 24\}$$

Demolition and quarry blasting are considered to be identical (and in both cases are negligible as described in Section 4.6). The cement manufacturing process is assumed to be identical from that point onwards, regardless of raw material source, in terms of specific energy inputs for thermal and electrical energy with the exception of process benefits of unreacted cement.

Unreacted cement contributes to the reduction of $CO_2$ emissions in three ways in this scenario: increased output due to raw material to clinker ratio; reduced thermal input due to non-carbonated raw material input; and reduced calcination factor due to non-carbonated raw material input.

#### 4.7.3.1 Unreacted Cement Benefits in Raw Material Substitution Scenario

As previously mentioned, unreacted cement contributes to the reduction of manufacturing $CO_2$ emissions in three ways, specifically: increased output due to raw material to clinker ratio; reduced thermal input due to non-carbonated raw material input; reduced calcination factor due to non-carbonated raw material input; and reduced specific electrical demand relative to material output. The following sections describe these benefits in detail and how such benefits are calculated in the model.

#### 4.7.3.2 Increased Output Due to Raw Material to Clinker Ratio

In order to produce 1 kg of clinker, 1.7 kg of raw material is required (Nisbet et al., 2002) with a minimum raw material input of 1.525 kg if accounting only for the mass of $CO_2$ emissions as per Equation 23. The additional impurities that would exist in limestone would be expected to exist in concrete (considering 90% of the concrete would be aggregate that is likely limestone or a derivative of limestone). As such, 1.525 kg is used as the amount of raw material input that would be substituted with demolished concrete.

The following equation is then used to determine the raw material to clinker ratio:

***Adjusted Clinker Output (ACO)***

= *[RM:CLK * (1 – (% unreacted cement * % cement in concrete)]/RM:CLK]* + *(RM:CLK * % unreacted cement * % cement in concrete)*

that can be simplified as follows:

= *[1 – (% unreacted cement * % cement in concrete)]* + *(RM:CLK * % unreacted cement * % cement in concrete)] [Equation 25]*

*Where:*

***RM:CLK Ratio*** = *Raw Material to Clinker Ratio (default value is 1.525 as explained above)*
***% unreacted cement*** = *as per Eq. 24*

Equation 25 can be best explained as two distinct parts. The first part of the equation, *1 – (%unreacted cement * % cement in concrete),* represents the portion of the cement that has not reacted with $CO_2$ and is therefore not a carbonated material. The second part of the equation, *RM:CLK * % unreacted cement * % cement in concrete,* represents the portion of the concrete that is fully carbonated either due to the carbon uptake of the cement portion or based on the fine or course aggregate that is expected to have similar chemistry as raw material for cement manufacturing.[6]

As an example, if the concrete in question contains 10% cement and 60% of the cement has reacted then the ACO, as per Equation 25, is:

[6] The fine and course aggregate material is expected to be calcium carbonate material with fine aggregate being manufactured sand

ACO = [1 – (%unreacted cement * % cement in concrete)] + (RM:CLK * % unreacted cement * % cement in concrete)]

= [1 – (0.4 *0.1)] * [(1.525 * 0.4 * 0.1)]

= 0.96+0.061

= 1.021

Therefore, 1.525 kg of raw material would produce 1.021 kg of clinker. Dividing each side by the result would give a RM:Clinker Ratio of 1.494:1 – meaning that 1.494 kg of raw material is need to produce 1 kg of clinker if 4% of the raw material is unreacted cement. The rationale for this is that the unreacted cement would pass through the system without decarbonation, so the capacity that would be consumed by a carbonated material (limestone or carbonated cement) would be higher as demonstrated by previous research (De Schepper et al., 2014).

Figure 4.7 provides a visual representation of Equation 25 demonstrating the sample equation versus the baseline scenario to highlight how additional mass of clinker output results from non-carbonated material for the same total mass of raw material input.

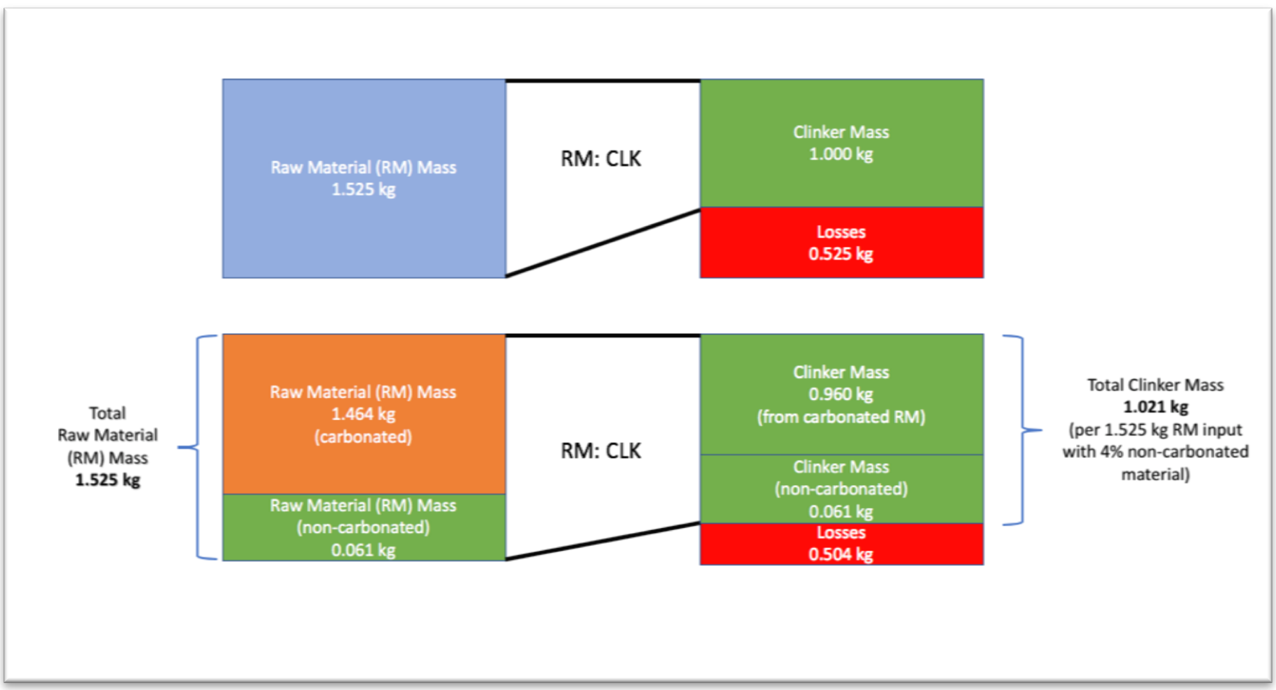


*Figure 4.7: Visual Representation of Adjusted Clinker Output (ACO)*

For the purpose of the model, the RM: CLK Ratio is used as presented in Equation 25 – meaning that the denominator for specific calculations is adjusted to account for the unreacted cement. From the example above, the model would use an Adjusted Clinker Output (ACO) of 1.021 kg. The ACO is used to determine the thermal and calcination emission reduction by dividing the current thermal input and calcination factor by the ACO determined in Equation 25.

### 4.7.3.3 Reduced Thermal Input Due to Non-Carbonated Raw Material

Thermal demand is further reduced due to non-carbonated raw materials as the emissions are based on the system output (namely 1 kg of clinker) which, based on the results of Equation 25, would be increased due to the availability of unreacted cement. Thermal energy in a kiln system is consumed for the chemical conversion of mineral compounds to clinker which is not required for the portion of material that is already in the desired chemical form. As such, it is expected that the amount of thermal energy proportional to the amount of unreacted cement would be eliminated. In addition, the amount of clinker produced would be increased due to the ACO further reducing the specific thermal consumption. It should be noted that the moisture content of limestone and crushed concrete is expected to be the same – therefore eliminating the need to correct for additional thermal energy or mass associated with moisture content[7].

Building on the previous example, if the concrete has 10% cement w/w and no cement has reacted then 1.525 kg of raw material will produce 1.021 kg of clinker. However, only 96% of the raw material (concrete) entering the system requires thermal processing which reduced the thermal demand by 4% in addition to producing the additional 0.021 kg of clinker.

The amount of thermal demand can be calculated as follows:

$$\boldsymbol{Adjusted\ Thermal\ Energy\ Consumption(MJ/t\ clinker)}$$

$$= \frac{Thermal\ Energy\ Cons.(MJ/t\ clinker) * (1 - \%\ unreacted\ cement * \%\ cement\ in\ concrete\ )}{ACO} \quad \textbf{\{Equation 26\}}$$

*Where:*

***Thermal energy consumption (MJ / t clinker)*** *– WBCSD: 93AG - Thermal energy consumption - Weighted average | including drying of fuels - Grey clinker (MJ / t clinker)*
***% unreacted cement*** *= results of Equation 24*
***ACO*** *= Adjusted Clinker Output {Equation 25)*

Although the reduction is theoretically valid, it has not been proven in application. As such, Equation 27 represents a condition where the thermal energy consumed by unreacted cement and fully carbonated raw material is the same – in other words, only the change in the raw material to clinker ratio due to non-carbonated material presence is considered.

$$\boldsymbol{Adjusted\ Thermal\ Energy\ Consumption_{ACO\ only}\ (MJ/t\ clinker) =}$$

$$\frac{Thermal\ Energy\ Consumption\ (MJ/t\ clinker)}{ACO} \quad \textbf{\{Equation 27\}}$$

[7] In fact, raw material moisture is shown to be higher for limestone compared to concrete (Albayati, Yasir Johansson, 2017; WBCSD, 2005)– however, the reference for concrete is in a lab which, as a result of outdoor storage, may increase to similar levels as natural limestone.

*Where:*

***Thermal energy consumption (MJ / t clinker)*** *– WBCSD: 93AG - Thermal energy consumption - Weighted average | including drying of fuels - Grey clinker (MJ / t clinker)*
***ACO*** = *Adjusted Clinker Output [Equation 25]*

Figure 4.8 provides a visual representation of Equation 26 demonstrating the portion of raw material input required thermal process building on the example used in the previous section for a concrete with 10% cement content that is 60% recarbonated.

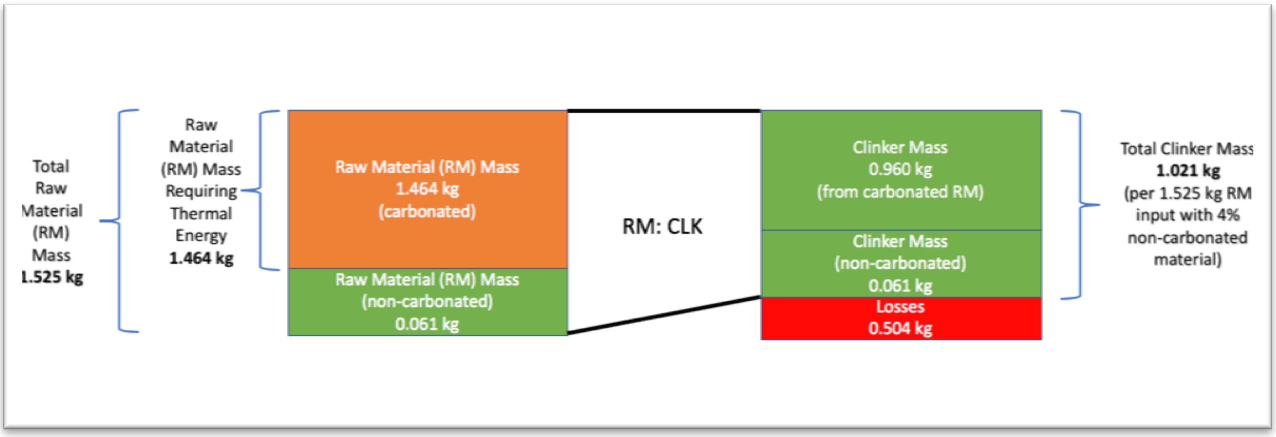


*Figure 4.8: Visual Representation of Adjusted Thermal Energy Demand*

### 4.7.3.4 Reduced Calcination Factor Due to Non-Carbonated Raw Material

Calcination emissions can be calculated as a direct reduction benefit from unreacted cement since there is no associated $CO_2$ emission to release from the material. As such, the new calcination emissions associated with the introduction of demolished concrete:

$$\boldsymbol{Adjusted\ Calcination\ Factor}\ (\boldsymbol{kg\ CO2/t\ clinker}) = \frac{Calcination\ Factor}{ACO}\ \textit{\{Equation 28\}}$$

*Where:*

***Calcination Factor*** = *result of Equation 1*
***ACO*** = *Adjusted Clinker Output {Equation 25}*

Continuing from the previous example of 10% cement in concrete with 40% cement content unreacted – it is both theoretically and practically accurate that no calcination emissions will be released from any unreacted cement (no $CO_2$ to release) and that clinker production will increase from the same input as calculated with Equation 25 – specifically 1.525 kg of raw material will produce 1.021 kg clinker.

#### 4.7.3.5 Reduction in Electrical Demand

Electrical demand is further reduced as the same amount of electrical energy would be consumed but for a greater amount of clinker output. This benefit is considered only through the end of clinker production as, after this point, the same unit of clinker would enter the cement manufacturing process and any electrical demand would be consistent regardless of the raw material origins.

The electrical energy benefits associated with non-carbonated raw material inputs can be calculated as follows:

***Adjusted Electrical Demand (kWh/t clinker)*** = *Power consumption up to and including clinker production/ACO* ***{Equation 29}***

*Where:*

1. ***Power consumption up to and including clinker production (kWh / t clinker)*** = *WBCSD: 33eAGW - Power consumption up to and including clinker production - Weighted average | Grey and white clinker (kWh / t clinker)*
2. ***ACO*** = *adjusted clinker output [Equation 25]*

#### 4.7.3.6 Calculation of Additive $CO_2$ for Raw Material Substitution Scenario

Based on the derivation of Equation 25 through 29, the additive $CO_2$ emissions associated with the raw material substitution scenario can be calculated as follows:

***Additive[8] $CO_2$ (kg/t cement)***

$$= (ACF + Adj.Therm. * Carbon\ Intensity\ of\ Fuel\ Mix) * \%\ clinker\ in\ OPC + \left(Elec.F * (Adj.Elec.Demand + Elec.Demand\ Cement)\right)$$

***{Equation 30}***

*Where:*

1. ***ACF*** = *Adjusted Calcination Factor [Equation 28]*
2. ***Adj. Therm*** = *Adjusted Thermal Energy Consumption [Equation 27]*
3. ***Carbon Intensity of Fuel Mix*** = *WBCSD*: 593AG - Carbon intensity of the fuel mix - Weighted average | Grey clinker (g $CO_2$ / MJ) divided by 1000*
4. ***% clinker in OPC*** = *1 - % Mineral additives to produce Portland Cement - WBCSD: 12AG - Mineral components used to produce Portland cement - Weighted average | Grey cement (% volume of cements)*
5. ***Elec. F*** = *Electricity $CO_2$ factor (kg $CO_2$/kwh) | Obtained from jurisdictional electricity provider*
6. ***Adj. Elec. Demand*** = *Adjusted Electrical Demand [Equation 29]*

[8] "additive" rather than "net" is used as "net emissions" has an existing meaning in cement nomenclature referring to benefits associated with use of alternative fuels in cement facilities versus alternative disposal options.

7. ***Electrical Demand Cement*** = *Electricity use (for entire facility – kwh/t clinker) – WBCSD: 33AGW - Cement plant power consumption - Weighted average | Grey and white cement (kWh / t cement) minus Power consumption up to and including clinker production (kWh / t clinker) - WBCSD: 33eAGW - Power consumption up to and including clinker production - Weighted average | Grey and white clinker (kWh / t clinker)*

The amount of $CO_2$ that is taken up by the concrete during its initial service life is excluded as any $CO_2$ taken up will be released with the introduction of the crushed concrete into the thermal process.

### 4.7.4 Clinker Substitution Scenario

The Clinker Substitution scenario considers the return of concrete to the cement mill process displacing clinker used for cement manufacturing. This entry point avoids the entire thermal process of the cement manufacturing which represents 99%[9] of the $CO_2$ emissions.

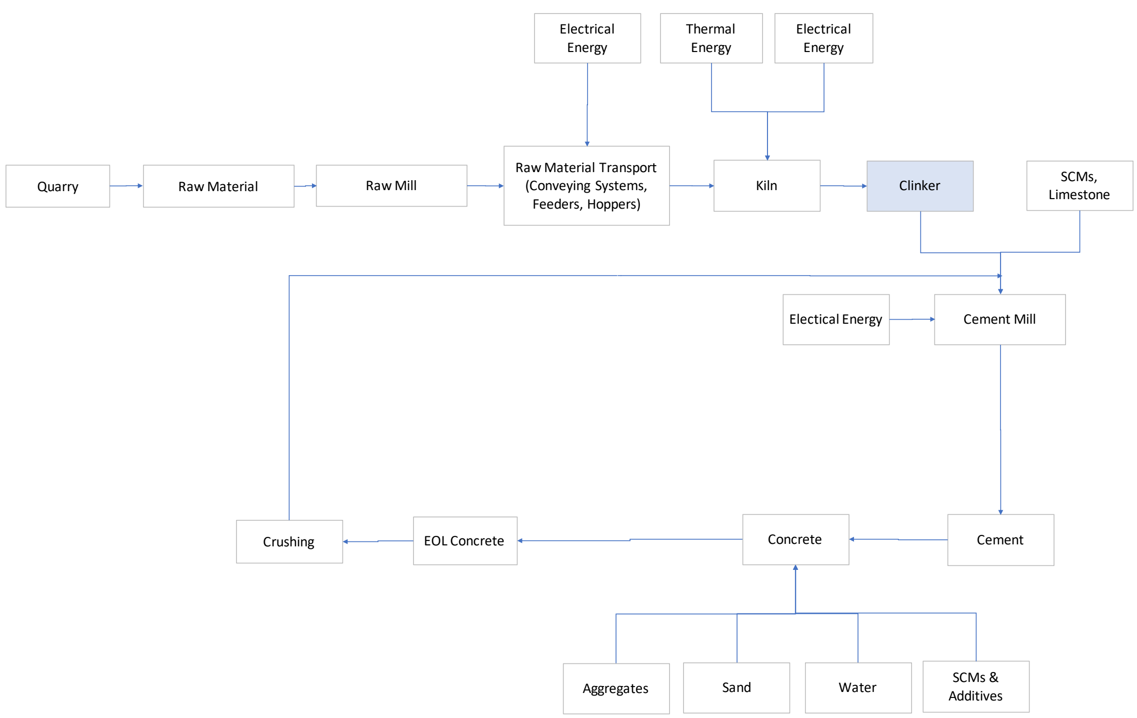


*Figure 4.9: Process Flowchart for Clinker Substitution*

Figure 4.9 shows the flow of EOL concrete to the clinker process. This Clinker Substitution, however, has a very strict limit with respect to input. EOL concrete that is returned into this portion of the process must not have a non-reactive (carbonated) quantity that exceed the

[9] This value represents the Canadian example but is consistent with expectation of clinker manufacturing (kiln process) excluding transportation and with a (relatively) modern electricity infrastructure.

jurisdiction limits – meaning that any carbonated portion of the concrete both as aggregate and recarbonated cement must be less than or equal to the jurisdictional limit. To reduce the total additive carbon, this maximum jurisdictional limit is built into the model to determine the amount of clinker substituted.

#### 4.7.4.1 Maximum Clinker Substitution

Based on the aforementioned condition, the upper limit for clinker substitution is based on the maximum percentage of limestone substitution permitted by regulatory bodies. This value can be adjusted based on jurisdictional building codes but for the purpose of the model a value of the Canadian standard of 15% limestone (Cement Association of Canada, 2020) is used to compare to a baseline scenario of actual limestone substitution.

This limitation is calculated as follows:

$$\boldsymbol{clinker\ displacement\ from\ EOL\ concrete\ limit\ \left(\frac{kg}{kg}\right)} = \frac{unreacted\ clinker\ x\ jurisdicational\ limestone\ limit}{1 - unreacted\ clinker}$$

$$\{\boldsymbol{Equation\ 31}\}$$

**Where:**

***unreacted clinker* (expressed as a %)** = % clinker in OPC * % cement in concrete * % unreacted cement ***{Equation 32}***
***jurisdictional limestone limit*** (expressed as a %) = maximum allowable limestone substitution for the jurisdiction

It should be noted that '*clinker in OPC*' in Equation 32 represents this value for the current production facilities rather than clinker in OPC of the concrete being repurposed. However, considering the focus on limestone addition as a key driver for $CO_2$ reduction by the cement industry, it is highly unlikely that future cements would have more rather than less limestone addition. An increase in limestone addition over time would result in a conservative (lower) value for Equation 31 meaning that the upper limit would be respected.

Equation 31 can be used if a facility/jurisdiction is maximizing limestone addition up to the jurisdictional limit. For any amount that is lower than the jurisdiction limit, Equation 31 is adjusted as follows:

$$\boldsymbol{clinker\ displacement\ from\ EOL\ concrete\ \left(\frac{kg}{kg}\right)} = \frac{unreacted\ clinker\ x\ limestone\ addition}{1 - unreacted\ clinker}$$

***{Equation 33}***

**Where:**

***unreacted clinker*** (expressed as a %) = clinker in OPC x % cement in concrete x % unreacted cement {Equation 32} – *same as equation 31*
***limestone addition*** (expressed as a %) = limestone addition to cement at the production facility

The % *unreacted cement* in Equation 32 is actually a value for the available CaO since Equation 24 calculated this value based on maximum $CO_2$ uptake potential less actual $CO_2$ uptake at the time of assessment. This means that the calculation determines the percentage of cementitious material in the concrete that is still available to uptake $CO_2$ – namely, CaO.

Equations 31 and 33 are derived as follows:

$$\frac{unreacted\ clinker\ in\ EOL\ concrete}{reacted\ material\ in\ EOL\ concrete} = \frac{clinker\ in\ cement}{limestone\ in\ cement}$$

$$\frac{unreacted\ clinker * limestone\ in\ cement}{1 - unreacted\ clinker} = \ clinker\ in\ cement$$

Solving for *clinker in cement* whether for a maximum value based on the jurisdictional limit as in Equation 31 or for the actual use of limestone in cement as in Equation 33, provides the amount of clinker that does not require production. The upper boundary of this substitution is limited by the proportion of carbonated material that will be entering the system along with the clinker.

Using Equation 33, the total amount of EOL concrete in clinker represents the amount of clinker that does not require production – an activity, as mentioned at the start of this section, that represents 99% of the $CO_2$ emissions associated with the cement manufacturing process from cradle-to-gate.

### 4.7.4.2 Calculation of Additive $CO_2$ for Clinker Substitution Scenario

The Additive $CO_2$ for the Clinker Substitution Scenario (as presented in Equation 35 below) represents the amount of clinker that will still require production even with the introduction of EOL concrete as a substitute. Practically, this only requires the reduction of clinker manufacturing by the amount calculated in Equation 33.

Equation 34 presents the calculation Adjusted Percentage (%) in OPC (APOPC)[10].

***APOPC (%)*** = *% clinker in OPC - clinker displacement from EOL concrete* ***{Equation 34}***

*Where:*

***% clinker in OPC*** = *value calculated in Equation 3*
***clinker displace from EOL concrete***= *value calculated in Equation 33*

[10] Adjusted Clinker Factor is not used since Clinker Factor is a defined term in the cement industry representing the percentage of clinker in cement.

With the APOPC, the Additive $CO_2$ value for clinker substitution can be calculated based on the reduced throughput of material in the thermal process as follows:

***Additive $CO_2$ (kg/t cement)*** = *[APOPC * (Calcination Factor* + *(Thermal energy consumption * Carbon intensity of fuel mix)]* + *(Elec. F * Elec. Facility)* ***{Equation 35}***

Where:

1. ***APOPC*** = *value calculated in Equation 33*
2. ***Calcination Factor*** *as calculated in Equation 1 in kg $CO_2$ per tonne of clinker*
3. ***Thermal energy consumption (MJ / t clinker)*** *– WBCSD: 93AG - Thermal energy consumption - Weighted average | including drying of fuels - Grey clinker (MJ / t clinker)*
4. ***Carbon intensity of the fuel mix (CO2 / MJ)*** *– WBCSD: 593AG - Carbon intensity of the fuel mix - Weighted average | Grey clinker (g CO2 / MJ)* ***/ 1000***
5. ***Thermal Process*** *is Thermal energy consumption (MJ / t clinker) x Carbon intensity of the fuel mix (kg CO2 / MJ)] on-site power generation - Grey clinker (kg $CO_2$ / t clinker) as a direct input value into the model.*
6. ***Elec. F*** = *Electricity $CO_2$ factor (kg $CO_2$/kwh) | Obtained from jurisdictional electricity provider*
7. ***Elec. Facility*** = *Electricity use (for entire facility – kwh/t clinker) – WBCSD: 33AGW - Cement plant power consumption - Weighted average | Grey and white cement (kWh / t cement)*

### 4.7.5 Cement Substitution Scenario

The Cement Substitution scenario considers the return of concrete to the concrete plant to offset the amount of cement used in the manufacturing of concrete. Although this scenario is sensible it is practically impossible as the amount of concrete used would always displace more than 100% of the input capacity. The following example demonstrates why such an application is impossible to implement:

Considering the previous example of one cubic meter of concrete with S.G. of 2.7 containing 300 kg of cement, in other words 2400 kg of non-cementitious material and 300 kg of cementitious material. It can be assumed that the moment the concrete is poured it begins to absorb carbon dioxide and in turn, reducing the percentage of available cementitious material. If at any point beyond the initial pour, the concrete is crushed and used in a new cubic meter of concrete it will contain more than 2400 kg of non-cementitious material which would mean that the entire cubic meter would not have sufficient cementitious material to produce a new cubic meter of concrete with the same design specification. Therefore, unless the original design called for more cement (eg. 400/500/600 kg per cubic meter) and the secondary use is 300 kg, then the amount of unreacted cement would never suffice.

Based on this, the cement substitution scenario is excluded from the assessment.

### 4.7.6 Aggregate Substitution Scenario

The Aggregate Substitution scenario considers the use of EOL concrete in aggregate application – the most common field application consisting of crushing EOL concrete for use as fill or base material.

Unlike the previous scenarios, no cement production is displaced but rather the benefit is associated with continued uptake of $CO_2$ until all available cement is fully recarbonated. Recycled Concrete Aggregate (RCA) use in concrete, in practice, ranges from 10% to 45% aggregate substitution (Klee, 2009). While RCA can substitute virgin aggregate, the "recycled concrete aggregate has cement in it. When reused in concrete it tends to have higher water absorption and can have lower strength than virgin aggregate" and therefore, 'sometimes more cement is needed' (Klee, 2009). As such, the benefit of EOL concrete for aggregate is considered strictly related to continued $CO_2$ uptake regardless of application.

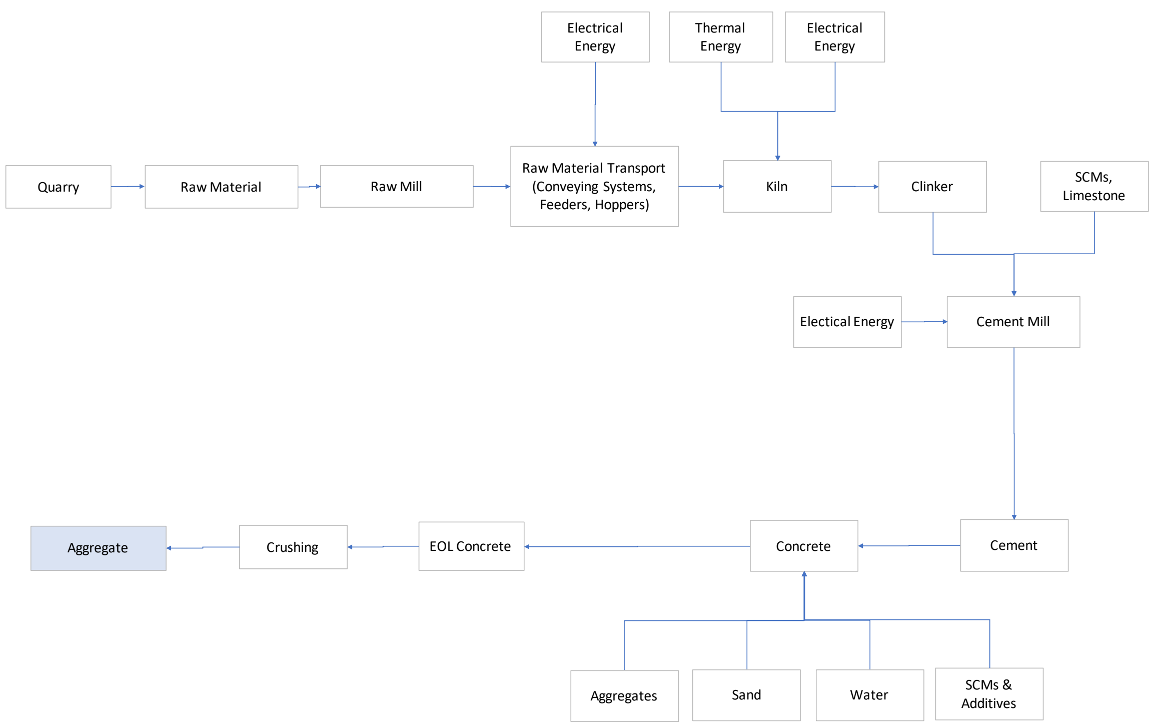


*Figure 4.10: Additive $CO_2$ Model for Aggregate Substitution Scenario*

The aggregate scenario represents carbon capture and utilization (CCU). As previously discussed, given sufficient time all the available CaO in the cement will recarbonate. However, as the rate of that recarbonation is correlated to surface area that is, in turn, affected by aggregate size in accordance to *Equation 8* – aggregate size is the primary variable in this scenario.

Numerous studies of carbon emissions associated with EOL concrete for aggregate substitution have been evaluated ((De Schepper et al., 2014; Di Maria et al., 2018; Kjellsen et al., 2005; Possan et al., 2016; Xi et al., 2016). Likely the most common application of EOL concrete, this scenario is an important comparison to the raw material and clinker substitution due to the prevalence of study.

The model outlined in Figure 4.10 continues from the end-of-life of the primary use by considering the ***kg $CO_2$/t cement (additive) from primary use***. This represents the kg $CO_2$/t of cement from manufacturing as well as the $CO_2$ uptake during the service life of the concrete. At the end-of-life of the primary use, the concrete structure is demolished and crushed.

Demolition is a complex and variable process depending on the type of concrete applications. It is assumed that the demolition is necessary as an upgrade or replacement and demolition would take place regardless of the final fate of the existing materials. The model commences evaluation of impact at the completion of demolition with crushing. It is assumed that crushing is not required for disposal of material so any use of crushing equipment would be an additional input.

Crushing equipment is assumed to be electrical to compare to the other scenarios and is consistent with the trend of available industry equipment (Jankovic, 2015; Sankvik, 2019) . Similar to the raw material and clinkers scenarios, transportation is excluded based on the rationale provided in Section 4.6.

All other inputs in the aggregate substitution model are consistent with the raw material and clinker substitution model with the exception of aggregate surface area which is calculated as follows:

**Aggregate surface area ($m^3$) =** $\frac{volume\ of\ concrete}{volume\ of\ aggregate} * surface\ area\ of\ aggregate$ ***{Equation 36}***

As the model is designed to assess one cubic meter of concrete and with the assumption that the aggregate is cubical in shape, the above equation can be simplified to:

***Aggregate surface area ($m^3$) =*** $\frac{1}{aggregate\ size\ (one\ side)^3} * aggregate\ size\ (one\ side)^2 * 6$

$= \frac{6}{aggregate\ size\ (one\ side)}$ ***{Equation 37}***

*Where:*

***Volume of concrete*** = *volume in cubic meters*
***Aggregate size (one side)*** = *measurement of one side as the aggregate is assumed to be cubical in shape*
***6*** *represented the number of sides*

The aggregate size calculated with Equation 37 allows for the evaluation of uptake resulting from the new surface area exposed as a result of demolition and crushing. In order to accurately capture the depth of $CO_2$ penetration relative to time as per Equation 8, the surface area is separated in two components: the original surface area and the new surface area. The new surface area is the result of Equation 37 less the original surface area used for Equation 8. $CO_2$ uptake for the new surface area is calculated using Equation 8. $CO_2$ uptake for the old surface area (ie. the area that has been exposed during the initial service life of the concrete) is calculated as follows:

*Additional $CO_2$ uptake (kg)* = *$CO_2$ uptake (new)$_{t+1}$ - CO2 uptake (previous)$_t$* ***{Equation 37}***

*Where:*

***$CO_2$ uptake (new)*** *is calculated using Equation 8 with the* *<u>year</u>* *value set to the end of the time period being assessed*
***$CO_2$ uptake (previous)*** *is calculated using Equation 8 with the* *<u>year</u>* *value set to the end of the previous time period*
***t*** *represents the duration of the service life*
***t + 1*** *represents the next time period of the same duration as the service life*

For example, assuming the service life of concrete is set to 40 years with the goal of calculating the $CO_2$ uptake of the original surface after another 40 years once the concrete is used for aggregate. The *year* value of *$CO_2$ uptake (additional)* is set to 80 while the *year* value of *$CO_2$ uptake (previous)* is set to 40. This ensures that the power function of recarbonation is accurately calculated.

Equation 37 can be used to calculate the new surface area by adjusting the value associated with t as the new surface area is one time period behind – ie. service life is representative of the aggregate service life that commences at the time of demolition and crushing.

### 4.7.6.1 Calculation of Additive $CO_2$ for Aggregate Substitution Scenario

The time period in Equation 37 is representative of the service life of concrete. The service life of the aggregate can be considered to continue until full recarbonation. To accurately capture the benefit of aggregate substitution the model is designed to assess this in iterative time periods equal to the original service life. This is done to compare the additive $CO_2$ emissions between the various substitution scenarios in terms of the production of a new tonne of cement for identical time periods.

Based on this, additive $CO_2$ emissions associated with the aggregate substitution scenario are calculated as follows:

***Additive $CO_2$ (kg/t cement)*** = *kg $CO_2$/t cement – $CO_2$ uptake (original surface area) – $CO_2$ uptake (new surface area)* ***{Equation 38}***

*Where:*

***kg $CO_2$/t cement*** *represents the production of one tonne of cement*
***$CO_2$ uptake (original surface area)*** *represents the cumulative $CO_2$ uptake starting at t = 0*
***$CO_2$ uptake (original surface area)*** *represents the cumulative $CO_2$ uptake starting at t = 1*

The evaluation for aggregate requires the assessment of a new production cycle every service life period with the continued uptake of $CO_2$ by the aggregates taken out of service. The metric evaluated is the production of one tonne of cement less the benefit of carbon uptake of unreacted cement in recycled concrete aggregate to ensure a logical comparison to the raw material and clinker scenarios.

### 4.8 Conclusion

The scenario presented in Section 4.7 highlights the potential and limitation of substitution of end-of-life concrete in existing cement manufacturing processes. The carbon reduction benefit is strictly associated with the availability of unreacted cement in reducing energy and material inputs into the manufacturing of new cement. Since the end-of-life concrete is being thermally processed to produce clinker that would be indistinguishable from traditional clinker (as presented in Section 4.7.1), additional end-of-life concrete can be used to substitute clinker itself at the next stage of the process. In short, these options are not mutually exclusive and, as such, the model assesses the substitution of both raw materials and clinker in a circular material flow.

The same is not true with concrete and aggregates. End-of-life concrete (as shown in Section 4.7.5 – 4.7.6) will not practically displace cement input. The benefit of aggregate substitution is derived from the continued absorption of $CO_2$. It is expected that aggregates can eventually be introduced as raw material or clinker substitutes, however, any benefit that would be achieved from $CO_2$ uptake would be eliminated once the material is reintroduced back into the cement manufacturing process.

This chapter has outlined the scope, boundaries, calculations and assumptions of the model design that can be used to compare the additive $CO_2$ emissions for three scenarios in two components of the Carbon Hierarchy. Specifically, the model can be used to calculate Raw Material Substitution and Clinker Substitution within the *Stretch* component of the Carbon Hierarchy as well as Aggregate use in the *Sequester* component of the Carbon Hierarchy. *Carbon Uptake*, a unique attribute to cement is validated as an intermediary level between *Stretch* and *Sequester* by contributing to the reduction of additive $CO_2$ emissions in both. The conversion of all $CO_2$ related processes to a functional unit of kilograms of $CO_2$ per tonne of cement in the creation of this model will allow for quantification of all components within the Carbon Hierarchy and assessment of the gap to carbon neutrality for the cement industry.

The detailed model structure and formulae derived in this chapter are demonstrated in Chapter 5 with a sample application. Chapter 6 and 7 further assess the various applications of end-of-life concrete to empirically validate the order of the Carbon Hierarchy.

# Chapter 5

# Analytical Model

# Input and Output Structure

The following chapter presents a sample scenario of the model that was developed in Chapter 4 to calculate $CO_2$ uptake by cement during the service life of concrete, reintroduction of end-of-life concrete as raw material and clinker substitution in the cement manufacturing process or use of end of life concrete as aggregate. This chapter includes input and output tables for the aforementioned end-of-life options based on the sample scenario along with explanation for each. The specific values used throughout are based on a Canadian cement manufacturing scenario.

## 5.1 Model Inputs

The purpose of this chapter is to explain the output tables that are produced with each model run and associated additive $CO_2$ emissions. All inputs and associated formulas associated with the information in Table 5.1 are presented in Chapter 4. All references to "Equation" numbers are associated with Chapter 4 and "Line" numbers refer to Table 5.1 below to show the application of the model developed in Chapter 4.

Table 5.1 outlines the model inputs required to calculate the impact of material circularity in the cement manufacturing process. The tables use data for Canada based on a 20-year concrete life for one cubic meter of concrete with a thickness of 250 mm. The 20-year scenario is used for two reasons: 1) it is the expected short-end of the service life for applications such as concrete sidewalks (Rajani, 2002); 2) it allows for the demonstration of numerous iterations (five iterations to be specific) of production and uptake for a 100-year assessment. Table numbers throughout this chapter, with the exception of Table 5.1, reflect the sequential numbering system of tables in the model.

| Line | Input | Units | Value |
|---|---|---|---|
| 1 | Gross CO2 emissions (reference from WBCSD - see Line 37) | kg CO2/t clinker | 856 |
| 2 | Thermal energy consumption | MJ/t clinker | 3755 |
| 3 | Carbon intensity of fuel mix | g CO2/MJ | 85 |
| 4 | Power consumption up to and including clinker production | kWh/t clinker | 80 |
| 5 | Electrical Energy CO2 intensity | kg CO2/kWh | 0.15 |
| 6 | **Calcination Factor** | **kg CO2/t clinker** | **524.8** |
| 7 | Molecular Weight Calcium Oxide | g/mol | 56.08 |
| 8 | Molecular Weight Carbon Dioxide | g/mol | 44.01 |
| 9 | **CaO in clinker** | **%** | **65** |
| 10 | **% clinker in OPC** | **%** | **89** |
| 11 | **Mineral additive to produce Portland Cement** | % | 11.0 |
| 12 | **CaO in cement** | **%** | **57.85** |
| 13 | **% cement in concrete mix** | **%** | **11** |
| 14 | S.G. concrete | unitless | 2.7 |
| 15 | **Cement in Concrete** | **kg per m3** | **297** |
| 16 | Concrete thickness | mm | 250 |
| 17 | **Surface Area** | **m2** | **10** |
| 18 | T. Carb | unitless (default = 0.75) | 0.75 |
| 19 | Concrete age (ie. service years) | years | 20 |
| 20 | **Max CO2 uptake (absolute)** | **kg CO2 per m3 concrete** | **134.84** |
| 21 | **Max CO2 uptake (T. Carb restricted)** | **kg CO2 per m3 concrete** | **101.13** |
| 22 | **Thermal Process Factor** | **kg/t clinker** | **319.18** |
| 23 | Power consumption for entire facility (cement manufacturing) | kwh/t cement | 131 |
| 24 | Calcination Lower Limit | kg CO2/t clinker | 510.10 |
| 25 | Upper Substitution Limit (clinker substitution) | kg/t clinker | 16.47 |
| 26 | Jurisdictional Limestone Substitution Limit (% clinker displacement) | % | 15 |
| 27 | Limestone Addition | % | 4.0 |
| 28 | Limestone Addition Boundary (cannot exceed total mineral additives) | % | 4.0 |
| 29 | % electricity of full facility for crushing/grinding | constant | 22 |
| 30 | **Electrical Energy Consumption for crushing/grinding concrete for cement feed** | **kg CO2/t concrete (or /t cement - same thing at this point)** | **4.323** |
| 31 | Aggregate Size for EOL use | mm (assuming cubic shape for S.A purposes) | 22.4 |
| 32 | **Surface Area Change** | **m2** | **257.86** |
| 33 | Electrical Energy for Aggregate Production | kwh/t concrete | 1.50 |
| 34 | **Cement Amount in Concrete Mix** | **kg cement/t concrete** | **110.0** |
| 35 | **Electrical Energy for Aggregate Production** | **kwh/t cement** | **13.64** |
| 36 | **Electrical Energy Consumption for crushing/grinding concrete for aggregate** | **kg CO2/t cement** | **2.05** |
| 37 | *Gross CO2 emissions* | *kg CO2/kg cement* | 771 |
| 38 | Jurisdication | | Canada |

*Table 5.1: Model Input Table*

## 5.2 Base Case Scenario

Table 1 shows the calculated results for unbound $CO_2$ uptake per cubic meter of concrete. This calculation is based on the formulas presented in Chapter 4 with the same Input Factor as shown in Table A1 representing $CO_2$ penetration depth relative to concrete strength and utilization. The unbound calculation does not consider the potential limitation of uptake as per Line 20 in the input table. This means that all available CaO can react with $CO_2$ to reach 100% (T. Carb) uptake.

| Output (Table 1 - $CO_2$ uptake per $m^3$, unbound) | | | | |
|---|---|---|---|---|
| time (year) = 20 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 9.05 | 4.52 | 3.39 | 2.26 |
| Buried | 13.57 | 6.78 | 4.52 | 3.39 |
| Exposed | 22.61 | 11.31 | 6.78 | 4.52 |
| Sheltered | 45.23 | 27.14 | 18.09 | 11.31 |
| Indoors | 67.84 | 40.70 | 27.14 | 15.83 |

| Table A1: k value (mm) | | | | |
|---|---|---|---|---|
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 2 | 1 | 0.75 | 0.5 |
| Buried | 3 | 1.5 | 1 | 0.75 |
| Exposed | 5 | 2.5 | 1.5 | 1 |
| Sheltered | 10 | 6 | 4 | 2.5 |
| Indoors | 15 | 9 | 6 | 3.5 |

Table 1 results are calculated using Equation 8 as presented in Chapter 4:

$$\textbf{Total } \boldsymbol{CO_2} \textbf{ uptake } (\boldsymbol{kg}) = d * c * CaO * T.Carb * S.A. * \frac{M.CO_2}{M.CaO} \quad \text{\{Equation 8\}}$$

*where;*
*d = k value from Table A1/1000 * Line 19*
*c = Line 15*
*CaO = Line 12*
*T. Carb = Line 18*
*S.A = Line 17*
*$M.CO_2/M.CaO$ = Lines 8/Line 7*

Service life of 20 years is used for sample calculations throughout to demonstrate the model calculations with five iterations over a 100-year period. The calculations for the above equation are as follow for wet concrete <15 MPa (as a sample calculations).

$$CO_2\,uptake\left(\frac{kg}{m^3}\right)[unbound] = \frac{10}{1000} * \sqrt{20} * 297 * \frac{57.85}{100} * 0.75 * 10 * \frac{44.01}{56.08}$$

$$= 45.23\ kg\ CO_2/m^3\ concrete$$

Table 2 shows results of calculated values presented in Table 1 to ensure that the maximum amount of $CO_2$ uptake is restricted to the maximum potential if all CaO in cement reacts – in other words, the upper boundary is respected in accordance to Equation 11 in Chapter 4:

$$\boldsymbol{CO_2\ uptake\ (max\ kg)} = c * CaO * T.Carb * \frac{M.CO_2}{M.CaO}\ \textbf{\{Equation 11\}}$$

$$= 297 * \frac{57.85}{100} * 1 * \frac{44.01}{56.08}$$

$$= 134.84\ kg\ CO_2/m^3\ concrete$$

In the current example, the maximum amount of $CO_2$ uptake is 134.84 kg $CO_2/m^3$ concrete as calculated above and shown on Line 20 in Figure 1. Therefore, Table 1 and Table 2 in this scenario are identical as the maximum is not reached.

| Output (Table 2 - $CO_2$ uptake per $m^3$, max bound) | | | | |
|---|---|---|---|---|
| time (year) = 20 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 9.05 | 4.52 | 3.39 | 2.26 |
| Buried | 13.57 | 6.78 | 4.52 | 3.39 |
| Exposed | 22.61 | 11.31 | 6.78 | 4.52 |
| Sheltered | 45.23 | 27.14 | 18.09 | 11.31 |
| Indoors | 67.84 | 40.70 | 27.14 | 15.83 |

Table 3 shows the converted $CO_2$ uptake per cubic meter of concrete in Table 2 to the equivalent amount of $CO_2$ uptake per tonne of cement as calculated using Equation 21 in Chapter 4 (sample calculation for Sheltered, <15 MPa shown):

$$\boldsymbol{CO_2\ (kg\ uptake\ per\ tonne\ cement)} = \frac{CO_2\ \text{kg uptake per } m^3 \text{ concrete}}{c/1000}\ \textbf{\{Equation 21\}}$$

$$= \frac{45.23}{297/1000}$$

$$= 152.3$$

Tonnes of cement is the specific metric used for $CO_2$ output in Line 37 of Figure 1 and is the reference metric for the entire model. The values in Table 3 are the results of Table 2 values but controlled to the upper boundary of $CO_2$ uptake.

| Output (Table 3 - $CO_2$ uptake per tonne cement) | | | | |
|---|---|---|---|---|
| time (year) = 20 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 30.5 | 15.2 | 11.4 | 7.6 |
| Buried | 45.7 | 22.8 | 15.2 | 11.4 |
| Exposed | 76.1 | 38.1 | 22.8 | 15.2 |
| Sheltered | 152.3 | 91.4 | 60.9 | 38.1 |
| Indoors | 228.4 | 137.0 | 91.4 | 53.3 |

Table 4 shows the additive $CO_2$ emissions associated with the production of one tonne of cement as a combination of production emissions less $CO_2$ uptake during the initial service life (ie. first 20 years in this scenario) in accordance with Equation 20 in Chapter 4 (sample calculation for Sheltered, <15 MPa shown is shown below):

***Additive*[1] *$CO_2$ (kg/t cement)*** = $[(ther.\ process + calc.factor) * \%\ clinker\ in\ OPC] + (Elec.F\ x\ Elec.Facility) - CO_2\ uptake\ (per\ tonne)$ ***{Equation 19}***

*Where:*

1. *ther. process = Line 2 * Line 3/1000*
2. *calc. factor = Line 6*
3. *% clinker in OPC = Line 10*
4. *Elec. F = Line 5*
5. *Elec. Facility = Line 23*
6. *$CO_2$ uptake (kg per tonne of cement) = Table 3*

***Additive $CO_2$ (kg/t cement)*** = $[(ther.\ process + calc.factor) * \%\ clinker\ in\ OPC] + (Elec.F\ x\ Elec.Facility) - CO_2\ uptake\ (kg\ per\ tonne\ of\ cement)$

$$= \left[\left(3755 * \frac{85}{1000} + 524.8\right) * 0.89\right] + (0.15 * 131) - 152.3$$

= 619 *kg $CO_2$/t cement*

Additive $CO_2$ emissions are the comparable measure for all material circularity options resulting from the model.

[1] "additive" rather than "net" is used as "net emissions" has an existing meaning in cement nomenclature referring to benefits associated with use of alternative fuels in cement facilities versus alternative disposal options.

| Output (Table 4 - Baseline Scenario, Additive $CO_2$ per tonne of cement) | | | | |
|---|---|---|---|---|
| time (year) = 20 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 740 | 756 | 759 | 763 |
| Buried | 725 | 748 | 756 | 759 |
| Exposed | 695 | 733 | 748 | 756 |
| Sheltered | 619 | 679 | 710 | 733 |
| Indoors | 542 | 634 | 679 | 718 |

Tables 2C and 3C show the calculated results of $CO_2$ uptake per cubic meter ($m^3$) of concrete and per tonne of cement, respectively, with the 1.68% per millimeter of penetration error on a 100-year basis determined in Chapter 4. The error factors are calculated throughout on a 100-year basis but are not applied to the model assessment at each iteration. The error is calculated to allow for sensitivity analysis with detailed scenarios runs as an overall error (as will be presented in Chapter 7).

| Output (Table 2C - $CO_2$ uptake per $m^3$, max bound w/error) | | | | |
|---|---|---|---|---|
| time (year) = 20 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 8.74 | 4.45 | 3.35 | 2.24 |
| Buried | 12.88 | 6.61 | 4.45 | 3.35 |
| Exposed | 20.71 | 10.83 | 6.61 | 4.45 |
| Sheltered | 37.63 | 24.40 | 16.87 | 10.83 |
| Indoors | 50.74 | 34.55 | 24.40 | 14.90 |

| Output (Table 3C - $CO_2$ uptake per tonne cement with error) | | | | |
|---|---|---|---|---|
| time (year) = 20 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 29.43 | 14.97 | 11.28 | 7.55 |
| Buried | 43.38 | 22.27 | 14.97 | 11.28 |
| Exposed | 69.74 | 36.47 | 22.27 | 14.97 |
| Sheltered | 126.69 | 82.15 | 56.82 | 36.47 |
| Indoors | 170.85 | 116.32 | 82.15 | 50.16 |

The error factors are presented in Table B1.

| Table B1: Error (based on 1.68%/mm of k value) | | | | |
|---|---|---|---|---|
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 3.36 | 1.68 | 1.26 | 0.84 |
| Buried | 5.04 | 2.52 | 1.68 | 1.26 |
| Exposed | 8.4 | 4.2 | 2.52 | 1.68 |
| Sheltered | 16.8 | 10.08 | 6.72 | 4.2 |
| Indoors | 25.2 | 15.12 | 10.08 | 5.88 |

Table 4C shows the calculated results for the additive $CO_2$ emissions associated with the production of one tonne of cement as a combination of production emissions less $CO_2$ uptake adjusted for the error associated with uptake as per Table 3C.

| Output (Table 4C - Baseline Scenario, Additive $CO_2$ w/error) | | | | |
|---|---|---|---|---|
| time (year) = 20 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 741 | 756 | 760 | 763 |
| Buried | 727 | 749 | 756 | 760 |
| Exposed | 701 | 734 | 749 | 756 |
| Sheltered | 644 | 689 | 714 | 734 |
| Indoors | 600 | 654 | 689 | 721 |

Table 4D shows the calculated results for the percentage error of additive $CO_2$ as percentage difference between Table 4 and Table 4C. The percentage error in Table 4D reflects the full error of an additive $CO_2$ emission rather than just the uptake error calculated in 2C.

| Output (Table 4D - Baseline Scenario Error) | | | | |
|---|---|---|---|---|
| time (year) = 20 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 0.14% | 0.03% | 0.02% | 0.01% |
| Buried | 0.32% | 0.08% | 0.03% | 0.02% |
| Exposed | 0.91% | 0.22% | 0.08% | 0.03% |
| Sheltered | 3.97% | 1.34% | 0.57% | 0.22% |
| Indoors | 9.59% | 3.17% | 1.34% | 0.43% |

Tables 1 through 4 capture the information required to assess the additive $CO_2$ emissions associated with one tonne of cement during the initial service life of concrete.

## 5.3 Raw Material Substitution

Tables 5 through 10 show results of calculations for the additive $CO_2$ emissions associated with one tonne of cement in concrete application relative to a raw material substitution scenario as explained in Chapter 4.

Table 5 shows the calculated results for the percentage of unreacted cement in the concrete mix at the end of the concrete life (EOL) in accordance with Equation 24 in Chapter 4 (sample calculation for Sheltered, <15 MPa shown is shown below):

$$Unreacted\ cement\ (\%) = \frac{Max\ CO_2\ uptake\ (kg)\ \{Eq.11\} - Total\ CO_2\ uptake\ (kg)\ \{Eq.8\}}{Max\ CO_2\ uptake\ (kg)\ \{Eq.11\}}$$ ***{Equation 24}***

The results presented in Table 1 and Line 20 (Table 5.1) are calculated using Equation 8 and 11, respectively.

$$Unreacted\ cement\ (\%) = \frac{Line\ 20 - Table\ 1}{Line\ 20}$$

$$= \frac{134.84 - 45.23}{134.84}$$

$$= 0.66\ (\text{or } 66\%)$$

| Output (Table 5 - unreacted cement) | | | | |
|---|---|---|---|---|
| time (year) = 20 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 93% | 97% | 97% | 98% |
| Buried | 90% | 95% | 97% | 97% |
| Exposed | 83% | 92% | 95% | 97% |
| Sheltered | 66% | 80% | 87% | 92% |
| Indoors | 50% | 70% | 80% | 88% |

Utilizing the output of Table 5, Table 6 shows the calculation results for the adjusted clinker factor in accordance with Equation 25 in Chapter 4 (sample calculation for Sheltered, <15 MPa shown is shown below):

Adjusted Clinker Output (ACO) = [1 – (% unreacted cement * % cement in concrete)] + (RM:CLK * % unreacted cement * % cement in concrete)] ***{Equation 25}***

*Where:*

1. *% unreacted cement = Table 5*
2. *% cement in concrete = Line 13*
3. *RM:CLK = 1.525 (constant as explained in Chapter 4)*

Therefore (sample calculations for Sheltered, <15 MPa):

Adjusted Clinker Output (ACO) = [1 – (% unreacted cement * % cement in concrete)] + (RM:CLK * % unreacted cement * % cement in concrete)]

= [1 – (0.66*0.11)]+(1.525*0.66*0.11)

= 0.927+0.111

= 1.038 (unitless)

| Output (Table 6 - Adjusted Clinker Output) | | | | |
|---|---|---|---|---|
| time (year) = 20 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 1.054 | 1.056 | 1.056 | 1.057 |
| Buried | 1.052 | 1.055 | 1.056 | 1.056 |
| Exposed | 1.048 | 1.053 | 1.055 | 1.056 |
| Sheltered | 1.038 | 1.046 | 1.050 | 1.053 |
| Indoors | 1.029 | 1.040 | 1.046 | 1.051 |

Table 7A shows the calculated results for the adjusted thermal energy consumption due to reduced energy needs associated with the specific percentage of unreacted cement in accordance with Equation 26 in Chapter 4 (sample calculation for Sheltered, <15 MPa shown is shown below).

$$Adjusted\ Thermal\ Energy\ Consumption (MJ/t\ clinker)$$

$$= \frac{Thermal\ Energy\ Cons.(MJ/t\ clinker) * (1 - \%\ unreacted\ cement * \%\ cement\ in\ concrete\ )}{ACO}\ \textit{\{Equation 26\}}$$

*Where:*

1. $Thermal\ Energy\ Cons.(MJ/t\ clinker)$ = *Line 2*
2. *% unreacted cement = Table 5*
3. *% cement in concrete = Line 13*
4. *ACO = Table 6*

Therefore (sample calculations for Sheltered, <15 MPa):

$$Adjusted\ Thermal\ Energy\ Consumption (MJ/t\ clinker)$$

$$= \frac{Thermal\ Energy\ Cons.(MJ/t\ clinker)\ * (1 - \%\ unreacted\ cement\ *\ \%\ cement\ in\ concrete\ )}{ACO}$$

$$= \frac{3755 \ * (1 - 0.66 \ * \ 0.11 \ )}{1.038}$$

= *3353 MJ/t clinker*[2] *(3352 in Table 7A)*

| Output (Table 7A - Adjusted Thermal Energy Consumption) | | | | |
|---|---|---|---|---|
| time (year) = 20 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 3,197 | 3,178 | 3,174 | 3,169 |
| Buried | 3,216 | 3,188 | 3,178 | 3,174 |
| Exposed | 3,255 | 3,207 | 3,188 | 3,178 |
| Sheltered | 3,352 | 3,274 | 3,236 | 3,207 |
| Indoors | 3,451 | 3,332 | 3,274 | 3,226 |

Table 7B shows the calculated results for the upper boundary of the adjusted thermal energy consumption as presented in Chapter 4. This value is based on the increase clinker factor as presented in Table 6, capturing the benefit of additional material output for the same raw material input but not the benefit associated with reduced thermal energy needs due to unreacted cement as in Table 7A. This is referenced as an adjustment for increased clinker output only – "ACO only". Specifically, this is calculated in accordance with Equation 26 in Chapter 4 (sample calculation for Sheltered, <15 MPa shown is shown below).

$$Adjusted\ Thermal\ Energy\ Consumption_{ACO\ only}\ (MJ/t\ clinker)$$

$$= \frac{Thermal\ Energy\ Consumption\ (MJ/t\ clinker)}{ACO}$$ ***{Equation 27}***

= *3755/1.038*

= *3618 MJ/t clinker*[2] *(3616 in Table 7B)*

| Output (Table 7B - Adjusted Thermal Energy Consumption, ACO only) | | | | |
|---|---|---|---|---|
| time (year) = 20 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 3,563 | 3,557 | 3,555 | 3,553 |
| Buried | 3,570 | 3,560 | 3,557 | 3,555 |
| Exposed | 3,583 | 3,566 | 3,560 | 3,557 |
| Sheltered | 3,616 | 3,589 | 3,576 | 3,566 |
| Indoors | 3,650 | 3,609 | 3,589 | 3,573 |

[2] table values are more precise as a result of unrounded values being carried throughout the calculations in the excel model. This value is manually calculated using the equations and values shown resulting in minor difference.

Table 8 shows the calculated results for the adjusted calcination factor based on the percentage of unreacted cement present in the raw material in accordance with Equation 28 in Chapter 4 (sample calculation for Sheltered, <15 MPa shown is shown below).

Adjusted Calcination Factor $(kg\ CO2/t\ clinker) = \frac{Calcination\ Factor}{ACO}$ ***{Equation 28}***

Where:

1. Calcination Factor = Line 1
2. ACO = Table 6

Therefore (sample calculations for Sheltered, <15 MPa):

$$\text{Adjusted Calcination Factor } (kg\ CO2/t\ clinker) = \frac{Calcination\ Factor}{ACO}$$

$$= \frac{524.8}{1.038}$$

= 506 *kg* $CO_2$*/t clinker*[3] *(505.4 in Table 8)*

| Output (Table 8 - Adjusted Calcination Factor) | | | | |
|---|---|---|---|---|
| time (year) = 20 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 498 | 497 | 497 | 497 |
| Buried | 499 | 498 | 497 | 497 |
| Exposed | 501 | 498 | 498 | 497 |
| Sheltered | 505 | 502 | 500 | 498 |
| Indoors | 510 | 504 | 502 | 499 |

Table 9 shows the calculated results for the adjusted electrical demand through the end of clinker production based on the availability of unreacted cement and associated adjusted clinker output (ACO) in accordance with Equation 29 in Chapter 4 (sample calculation for Sheltered, <15 MPa shown is shown below).

***Adjusted Electrical Demand (kWh/t clinker)*** = *Power consumption up to and including clinker production/ACO* ***{Equation 29}***

*Where:*

1. *Power consumption up to and including clinker production = Line 4*
2. *ACO* = Table 6

[3] table values are more precise as a result of unrounded values being carried throughout the calculations in the excel model. This value is manually calculated using the equations and values shown resulting in minor difference.

Therefore (sample calculations for Sheltered, <15 MPa):

***Adjusted Electrical Demand (kWh/t clinker)*** = *Power consumption up to and including clinker production/ACO*

*= 80/1.038*

*= 77 kwh/t clinker*

| Output (Table 9 - Adjusted Electrical Demand) | | | | |
|---|---|---|---|---|
| time (year) = 20 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 76 | 76 | 76 | 76 |
| Buried | 76 | 76 | 76 | 76 |
| Exposed | 76 | 76 | 76 | 76 |
| Sheltered | 77 | 76 | 76 | 76 |
| Indoors | 78 | 77 | 76 | 76 |

Table 10A shows the calculated results for the total additive $CO_2$ in kilograms per tonne of cement resulting from the substitution of virgin raw material with EOL concrete in accordance with Equation 30 in Chapter 4 (sample calculation for Sheltered, <15 MPa shown is shown below).

***Additive $CO_2$ (kg/t cement)***

$$= (ACF * Adj.Therm * Carbon\ Intensity\ of\ Fuel\ Mix) * \%\ clinker\ in\ OPC + \left(Elec.F * (Adj.Elec.Demand + Elec.Demand\ Cement)\right)$$ ***{Equation 30}***

*Where:*

1. *ACF = Table 8*
2. *Adj. Therm = Table 7A for Table 10A (Table 7B for Table 10B)*
3. *Carbon Intensity of Fuel Mix = Line 3/1000*
4. *% clinker in OPC = Line 10*
5. *Elec. F = Line 5*
6. *Adj. Elec. Demand = Table 9*
7. *Electrical Demand Cement = Line 23 – Line 4*

Therefore (sample calculations for Sheltered, <15 MPa):

***Additive $CO_2$ (kg/t cement)***

$$= (Adj.Therm. + ACF * Carbon\ Intensity\ of\ Fuel\ Mix) * \%\ clinker\ in\ OPC + \left(Elec.F * (Adj.Elec.Demand + Elec.Demand\ Cement)\right)$$

$= \left(505 + 3352 * \frac{85}{1000}\right) * 0.89 + \left(0.15 * (77 + 131 - 80)\right)$

= *(505+ 285)*0.89 + 19*

= *723 kg $CO_2$/t cement*[4] *(722 in Table 10A)*

| Output (Table 10A - Raw Material Scenario, Additive $CO_2$) | | | | |
|---|---|---|---|---|
| time (year) = 20 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 704 | 702 | 701 | 701 |
| Buried | 706 | 703 | 702 | 701 |
| Exposed | 711 | 705 | 703 | 702 |
| Sheltered | 723 | 713 | 709 | 705 |
| Indoors | 734 | 720 | 713 | 708 |

The values presented in Table 10A are utilized for comparison with other EOL concrete options with respect to the Carbon Hierarchy.

Table 10B shows the calculated results for the total additive $CO_2$ in kilograms per tonne of cement resulting from the substitution of virgin raw material with EOL concrete using Table 7B rather than 7A for the Adjusted Thermal Energy Consumption (ACO only) value. As in Table 10A, Equation 30 is used.

| Output (Table 10B - Raw Material Scenario, Additive $CO_2$) | | | | |
|---|---|---|---|---|
| time (year) = 20 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 732 | 730 | 730 | 730 |
| Buried | 733 | 731 | 730 | 730 |
| Exposed | 736 | 732 | 731 | 730 |
| Sheltered | 743 | 737 | 734 | 732 |
| Indoors | 750 | 741 | 737 | 734 |

Tables 5C through 10C incorporate the uptake error (1.68% per millimeter of penetration error on a 100-year basis) into the data for Tables 5, 6, 7A, 8, 9 and 10A.

[4] table values are more precise as a result of unrounded values being carried throughout the calculations in the excel model. This value is manually calculated using the equations and values shown resulting in minor difference.

| Output (Table 5C - unreacted cement w/error) | | | | |
|---|---|---|---|---|
| time (year) = 20 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 94% | 97% | 98% | 98% |
| Buried | 90% | 95% | 97% | 98% |
| Exposed | 85% | 92% | 95% | 97% |
| Sheltered | 72% | 82% | 87% | 92% |
| Indoors | 62% | 74% | 82% | 89% |

| Output (Table 6C - Adjusted Clinker Output w/error) | | | | |
|---|---|---|---|---|
| time (year) = 20 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 1.054 | 1.056 | 1.056 | 1.057 |
| Buried | 1.052 | 1.055 | 1.056 | 1.056 |
| Exposed | 1.049 | 1.053 | 1.055 | 1.056 |
| Sheltered | 1.042 | 1.047 | 1.051 | 1.053 |
| Indoors | 1.036 | 1.043 | 1.047 | 1.051 |

| Output (Table 7C - Adjusted Thermal Energy Consumption w/error) | | | | |
|---|---|---|---|---|
| time (year) = 20 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 3,196 | 3,178 | 3,173 | 3,169 |
| Buried | 3,214 | 3,187 | 3,178 | 3,173 |
| Exposed | 3,247 | 3,205 | 3,187 | 3,178 |
| Sheltered | 3,319 | 3,262 | 3,230 | 3,205 |
| Indoors | 3,376 | 3,306 | 3,262 | 3,222 |

| Output (Table 8C - Adjusted Calcination Factor w/error) | | | | |
|---|---|---|---|---|
| time (year) = 20 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 498 | 497 | 497 | 497 |
| Buried | 499 | 498 | 497 | 497 |
| Exposed | 500 | 498 | 498 | 497 |
| Sheltered | 504 | 501 | 500 | 498 |
| Indoors | 507 | 503 | 501 | 499 |

| Output (Table 9C - Adjusted Electrical Demand Factor w/error) | | | | |
|---|---|---|---|---|
| time (year) = 20 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 76 | 76 | 76 | 76 |
| Buried | 76 | 76 | 76 | 76 |
| Exposed | 76 | 76 | 76 | 76 |
| Sheltered | 77 | 76 | 76 | 76 |
| Indoors | 77 | 77 | 76 | 76 |

| Output (Table 10C - Raw Material Scenario, Additive $CO_2$ w/error) | | | | |
|---|---|---|---|---|
| time (year) = 20 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 704 | 702 | 701 | 701 |
| Buried | 706 | 703 | 702 | 701 |
| Exposed | 710 | 705 | 703 | 702 |
| Sheltered | 719 | 712 | 708 | 705 |
| Indoors | 725 | 717 | 712 | 707 |

Table 10D shows the calculated results including the percentage error of additive $CO_2$ as a percentage difference between Table 10A and Table 10C. The percentage error in Table 10D reflects the full error of additive $CO_2$ emissions for the Raw Material Substitution Scenario.

| Output (Table 10D - Raw Material Scenario Error) | | | | |
|---|---|---|---|---|
| time (year) = 20 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 0.0% | 0.0% | 0.0% | 0.0% |
| Buried | 0.0% | 0.0% | 0.0% | 0.0% |
| Exposed | 0.1% | 0.0% | 0.0% | 0.0% |
| Sheltered | 0.5% | 0.2% | 0.1% | 0.0% |
| Indoors | 1.2% | 0.4% | 0.2% | 0.1% |

## 5.4 Clinker Substitution

Tables 11 through 14 evaluate the additive $CO_2$ emissions associated with one tonne of cement in concrete application relative to a clinker substitution scenario as explained in Chapter 4.

Table 11 shows the calculated results for the percentage of unreacted clinker in concrete based on the unreacted cement values in Table 5 as well as data from Lines 10 and 13 from the input table, in accordance with Equation 32 in Chapter 4 (sample calculation for Sheltered, <15 MPa shown is shown below).

*unreacted clinker (%) = % clinker in OPC x % cement in concrete x % unreacted cement* ***{Equation 32}***

*Where:*

1. *% clinker in OPC = Line 10*
2. *% cement in concrete = Line 13*
3. *% unreacted cement = Table 5*

Therefore (sample calculations for Sheltered, <15 MPa):

*unreacted clinker (%) = % clinker in OPC x % cement in concrete x % unreacted cement* ***{Equation 32}***

*= 0.89 * 0.11 * 0.66*

*= 0.065 or 6.5%*

| Output (Table 11 - available unreacted clinker in concrete) | | | | |
|---|---|---|---|---|
| time (year) = 20 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 9.1% | 9.5% | 9.5% | 9.6% |
| Buried | 8.8% | 9.3% | 9.5% | 9.5% |
| Exposed | 8.1% | 9.0% | 9.3% | 9.5% |
| Sheltered | 6.5% | 7.8% | 8.5% | 9.0% |
| Indoors | 4.9% | 6.8% | 7.8% | 8.6% |

Table 12 shows the calculated results for kilograms of clinker that are displaced with EOL material based on available unreacted cement in concrete as per Table 11 restricted by the reacted cement corresponding to the limestone limit in cement from Line 27 in the input table. The values are calculated in accordance with Equation 33 in Chapter 4 (sample calculation for Sheltered, <15 MPa shown is shown below). Results in Table 12 are expressed in kilograms per tonne.

$$clinker\ displacement\ \left(\frac{kg}{kg}\right) = \frac{unreacted\ clinker\ x\ limestone\ addition}{1-unreacted\ clinker}\ \textbf{\{Equation 33\}}$$

*Where:*

1. *unreacted clinker = Table 11*
2. *limestone addition = Line 27*

Therefore (sample calculations for Sheltered, <15 MPa):

$$clinker\ displacement\ \left(\frac{kg}{kg}\right) = \frac{0.065\ x\ 0.04}{1-0.065}$$

$$= 0.0028\frac{kg}{kg} or\ 2.8\ kg/tonne$$

| Output (Table 12 - input to cement mill, clinker displacement kg per tonne) | | | | |
|---|---|---|---|---|
| time (year) = 20 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 4.0 | 4.2 | 4.2 | 4.3 |
| Buried | 3.9 | 4.1 | 4.2 | 4.2 |
| Exposed | 3.5 | 3.9 | 4.1 | 4.2 |
| Sheltered | 2.8 | 3.4 | 3.7 | 3.9 |
| Indoors | 2.0 | 2.9 | 3.4 | 3.8 |

Table 13 shows the calculated results for the adjusted percentage of clinker in OPC (APOPC) by subtracting the amount of clinker that can be introduced from EOL concrete within the upper boundary of limestone substitution from the original percentage of clinker in concrete as per Line 10 in the input table. The values are calculated in accordance with Equation 34 in Chapter 4 (sample calculation for Sheltered, <15 MPa shown is shown below).

*APOPC (%) = % clinker in OPC - clinker displacement from EOL concrete* ***{Equation 34}***

*Where:*

1. *% clinker in OPC = Line 10*
2. *clinker displacement from EOL concrete = Table 12/1000*

Therefore (sample calculations for Sheltered, <15 MPa):

*APOPC (%) = % clinker in OPC – clinker displacement from EOL concrete*

*= 0.89 – 0.0028*

*= 0.887 or 88.7%*

| Output (Table 13 - adjusted % clinker in OPC from operations) | | | | |
|---|---|---|---|---|
| time (year) = 20 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 88.6% | 88.6% | 88.6% | 88.6% |
| Buried | 88.6% | 88.6% | 88.6% | 88.6% |
| Exposed | 88.6% | 88.6% | 88.6% | 88.6% |
| Sheltered | 88.7% | 88.7% | 88.6% | 88.6% |
| Indoors | 88.8% | 88.7% | 88.7% | 88.6% |

Table 14A shows the calculated results for the total additive $CO_2$ in kilograms per tonne of cement based on substituting clinker with EOL concrete bound by the total amount of limestone addition in cement according to Equation 34 in Chapter 4 (sample calculation for Sheltered, <15 MPa shown is shown below).

***Additive $CO_2$ (kg/t cement)*** *= [APOPC * (Calcination Factor + (Thermal energy consumption * Carbon intensity of fuel mix)] + (Elec. F * Elec. Facility)* ***{Equation 35}***

Where:

1. *APOPC = Table 11*
2. *Calcination Factor = Line 6*
3. *Thermal energy consumption = Line 2*
4. *Carbon intensity of the fuel mix – Line 3/1000*
5. *Elec. F = Line 5*
6. *Elec. Facility = Line 23*

Therefore (sample calculations for Sheltered, <15 MPa):

***Additive $CO_2$ (kg/t cement)*** *= [APOPC * (Calcination Factor + (Thermal energy consumption * Carbon intensity of fuel mix)] + (Elec. F * Elec. Facility)*

*= [0.887 * (524.8 + (3755 * 85/1000)] + (0.15 * 131)*

*= 748.6 + 19.7*

*= 768 kg $CO_2$/t cement*

| Output (Table 14A - Clinker Substitution, Additive $CO_2$ w/o crushing) | | | | |
|---|---|---|---|---|
| time (year) = 20 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 767 | 767 | 767 | 767 |
| Buried | 768 | 767 | 767 | 767 |
| Exposed | 768 | 767 | 767 | 767 |
| Sheltered | 768 | 768 | 768 | 767 |
| Indoors | 769 | 768 | 768 | 768 |

Table 14B shows the calculated results of Table 14A including energy expenditure (and associated $CO_2$ emission) for material preparation similar to limestone preparation in the raw material mills to be introduced into the cement mill for intergrinding. The difference between Table 14A and 14B is insignificant in this example as limestone addition (Line 27) is only 4% resulting in very limited clinker displacement and, therefore, limited intergrinding of EOL concrete.

| Output (Table 14B - Clinker Substitution, Additive $CO_2$ w/crushing) | | | | |
|---|---|---|---|---|
| time (year) = 20 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 767 | 767 | 767 | 767 |
| Buried | 768 | 767 | 767 | 767 |
| Exposed | 768 | 768 | 767 | 767 |
| Sheltered | 768 | 768 | 768 | 768 |
| Indoors | 769 | 768 | 768 | 768 |

Tables 11C, 12C, 13C, 14C, and 14D incorporate the uptake error (1.68% per millimeter of penetration error on a 100-year basis) into the date for Tables 11, 12, 13, 14A, and 14B, respectively.

| Output (Table 11C - available unreacted clinker in concrete w/error) | | | | |
|---|---|---|---|---|
| time (year) = 20 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 9.2% | 9.5% | 9.5% | 9.6% |
| Buried | 8.9% | 9.3% | 9.5% | 9.5% |
| Exposed | 8.3% | 9.0% | 9.3% | 9.5% |
| Sheltered | 7.1% | 8.0% | 8.6% | 9.0% |
| Indoors | 6.1% | 7.3% | 8.0% | 8.7% |

| Output (Table 12C - input to cement mill, clinker displacement kg per tonne w/error) | | | | |
|---|---|---|---|---|
| time (year) = 20 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 4.0 | 4.2 | 4.2 | 4.3 |
| Buried | 3.9 | 4.1 | 4.2 | 4.2 |
| Exposed | 3.6 | 4.0 | 4.1 | 4.2 |
| Sheltered | 3.0 | 3.5 | 3.7 | 4.0 |
| Indoors | 2.6 | 3.1 | 3.5 | 3.8 |

| Output (Table 13C - adjusted % clinker in OPC from operations w/error) | | | | |
|---|---|---|---|---|
| time (year) = 20 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 88.6% | 88.6% | 88.6% | 88.6% |
| Buried | 88.6% | 88.6% | 88.6% | 88.6% |
| Exposed | 88.6% | 88.6% | 88.6% | 88.6% |
| Sheltered | 88.7% | 88.7% | 88.6% | 88.6% |
| Indoors | 88.7% | 88.7% | 88.7% | 88.6% |

| Output (Table 14C - Clinker Substitution, Additive $CO_2$ w/o crushing w/error) | | | | |
|---|---|---|---|---|
| time (year) = 20 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 767 | 767 | 767 | 767 |
| Buried | 768 | 767 | 767 | 767 |
| Exposed | 768 | 767 | 767 | 767 |
| Sheltered | 768 | 768 | 768 | 767 |
| Indoors | 769 | 768 | 768 | 768 |

| Output (Table 14D - Clinker Substitution, Additive $CO_2$ w/crushing and w/error) | | | | |
|---|---|---|---|---|
| time (year) = 20 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 767 | 767 | 767 | 767 |
| Buried | 768 | 767 | 767 | 767 |
| Exposed | 768 | 767 | 767 | 767 |
| Sheltered | 768 | 768 | 768 | 767 |
| Indoors | 769 | 768 | 768 | 768 |

Table 14E show the calculated results for the percentage error of additive $CO_2$ as a percentage difference between Table 14B and Table 14D. The percent error in Table 14D reflects the full error of additive $CO_2$ emissions rather than just the uptake error.

| Output (Table 14E - Clinker Substitution, Additive $CO_2$ error) | | | | |
|---|---|---|---|---|
| time (year) = 20 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 0.00% | 0.00% | 0.00% | 0.00% |
| Buried | 0.00% | 0.00% | 0.00% | 0.00% |
| Exposed | 0.01% | 0.00% | 0.00% | 0.00% |
| Sheltered | 0.03% | 0.01% | 0.00% | 0.00% |
| Indoors | 0.06% | 0.02% | 0.01% | 0.00% |

## 5.5 Aggregate Substitution

Tables 15 through 19 show results of calculations of the additive $CO_2$ emissions associated with one tonne of cement in concrete application relative to an aggregate substitution scenario as explained in Chapter 4.

Table 15 shows the calculated results for the remaining available $CO_2$ uptake per cubic meter of concrete at the end of the service life by subtracting Table 2 value from the maximum potential uptake as presented in Line 20 in the input table.

| Output (Table 15 - $CO_2$ uptake available to reach maximum/$m^3$ concrete) | | | | |
|---|---|---|---|---|
| time (year) = 20 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 125.8 | 130.3 | 131.4 | 132.6 |
| Buried | 121.3 | 128.1 | 130.3 | 131.4 |
| Exposed | 112.2 | 123.5 | 128.1 | 130.3 |
| Sheltered | 89.6 | 107.7 | 116.7 | 123.5 |
| Indoors | 67.0 | 94.1 | 107.7 | 119.0 |

Table 16A shows the calculated results for $CO_2$ uptake (without limit) for the original surface area of the concrete block in accordance with Equation 37 in Chapter 4 (sample calculation for Sheltered, <15 MPa shown is shown below).

*Additional $CO_2$ uptake (kg) = $CO_2$ uptake (new)$_{t+1}$ - CO2 uptake (previous)$_{t}$* ***{Equation 37}***

*Where:*

1. *$CO_2$ uptake (new) is calculated using Equation 8 with the year value set to the end of the time period being assessed*
2. *$CO_2$ uptake (previous) is calculated using Equation 8 with the year value set to the end of the previous time period*
3. *t represents the duration of the service life*
4. *t + 1 represents the next time period of the same duration as the service life*

Expanding on Equation 37 above:

*Additional $CO_2$ uptake (kg) = $CO_2$ uptake (new)$_{t+1}$ - CO2 uptake (previous)$_t$*

$$= [(d_2 - d_1) * c * CaO * T.Carb * S.A.* \frac{M.CO_2}{M.CaO}]$$

*where;*
*$d_2$ = k value from Table A1/1000 * (**Line 19** * **2**)*
*$d_1$ = k value from Table A1/1000 * (Line 19 * 1)*
*S.A. = Line 17*
*c = Line 15*
*CaO = Line 12*
*T. Carb = Line 18*
*$M.CO_2/M.CaO$ = Lines 8/Line 7*

Therefore (sample calculations for Sheltered, <15 MPa):

*Additional $CO_2$ uptake (kg)* $= [(d_2 - d_1) * c * CaO * T.Carb * S.A._1 * \frac{M.CO_2}{M.CaO}]$

$$= [\ (\frac{10}{1000} * (\sqrt{40} - \sqrt{20})\ ] * 297 * \frac{57.85}{100} * 0.75 * 10 * \frac{44.01}{56.08}$$

*= 18.73 kg $CO_2$ per $m^3$ of concrete*

| Output (Table 16A - $CO_2$ uptake per $m^3$, unbound, old surface area) | | | | |
|---|---|---|---|---|
| | time (year) = | Year 21 to year 40 | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 3.75 | 1.87 | 1.40 | 0.94 |
| Buried | 5.62 | 2.81 | 1.87 | 1.40 |
| Exposed | 9.37 | 4.68 | 2.81 | 1.87 |
| Sheltered | 18.73 | 11.24 | 7.49 | 4.68 |
| Indoors | 28.10 | 16.86 | 11.24 | 6.56 |

Table 16B shows the calculated results for $CO_2$ uptake (without limit) for the new surface area (S.A.) of the concrete block. The calculations are completed using Equation 37 with the appropriate variable inputs for $d_2$, $d_1$, and additional surface area (S.A.) as explained in Chapter 4.

*Additional $CO_2$ uptake (kg)* = $[(d_2 - d_1) * c * CaO * T.Carb * S.A._1 * \frac{M.CO_2}{M.CaO}]$

*where;*
*$d_2$ = k value from Table A1/1000 * (**Line 19 * 1**)*
*$d_1$ = k value from Table A1/1000 * (**Line 19 * 0**) {initial time period for new surface area}*
*S.A. = **Line 32***
*c = Line 15*
*CaO = Line 12*
*T. Carb = Line 18*
*$M.CO_2$/M.CaO = Lines 8/Line 7*

Therefore (sample calculations for Sheltered, <15 MPa):

*Additional $CO_2$ uptake (kg)* = $[(d_2 - d_1) * c * CaO * T.Carb * S.A._1 * \frac{M.CO_2}{M.CaO}]$

$$= [\ (\frac{10}{1000} * (\sqrt{20} - \sqrt{0})\ ] * 297 * \frac{57.85}{100} * 0.75 * 257.86 * \frac{44.01}{56.08}$$

= *1166 kg $CO_2$ per $m^3$ of concrete*

| Output (Table 16B - $CO_2$ uptake per $m^3$, unbound, new surface area) | | | | |
|---|---|---|---|---|
| | time (year) = | Year 21 to year 40 | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 233 | 117 | 87 | 58 |
| Buried | 350 | 175 | 117 | 87 |
| Exposed | 583 | 292 | 175 | 117 |
| Sheltered | 1,166 | 700 | 466 | 292 |
| Indoors | 1,749 | 1,050 | 700 | 408 |

Table 17 shows the summation of the total $CO_2$ uptake per cubic meter of concrete for the aggregates based on Table 16A and 16B bound by a maximum uptake potential in Line 20 at the end of the second time interval (ie. 40 years). For all summation values that exceed Line 20, the results are shown as the maximum uptake equal to Line 20.

| Output (Table 17 - total $CO_2$ uptake per $m^3$, max bound) | | | | |
|---|---|---|---|---|
| time (year) = 40 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 134.84 | 123.01 | 92.26 | 61.51 |
| Buried | 134.84 | 134.84 | 123.01 | 92.26 |
| Exposed | 134.84 | 134.84 | 134.84 | 123.01 |
| Sheltered | 134.84 | 134.84 | 134.84 | 134.84 |
| Indoors | 134.84 | 134.84 | 134.84 | 134.84 |

Table 18 shows the calculated results from Table 17 converted to the total kilograms of $CO_2$ uptake per tonne of cement for aggregates bound by a maximum uptake potential at the end of the second time interval (ie. 40 years). Table 17 and 18 both show that the maximum potential $CO_2$ uptake has been reached for certain applications and strengths. Therefore, the values shown in the tables are the maximum total $CO_2$ uptake per $m^3$ and per tonnes of cement, respectively.

| Output (Table 18 - $CO_2$ uptake per tonne cement, max bound) | | | | |
|---|---|---|---|---|
| time (year) = 40 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 453.99 | 414.18 | 310.64 | 207.09 |
| Buried | 453.99 | 453.99 | 414.18 | 310.64 |
| Exposed | 453.99 | 453.99 | 453.99 | 414.18 |
| Sheltered | 453.99 | 453.99 | 453.99 | 453.99 |
| Indoors | 453.99 | 453.99 | 453.99 | 453.99 |

Table 19A shows the calculated results for the total additive $CO_2$ in kilograms per tonne of cement based on utilizing EOL concrete as aggregates in accordance to Equation 38 in Chapter 4 as follows:

***Additive $CO_2$ (kg/t cement) =*** *kg $CO_2$/t cement – $CO_2$ uptake (original surface area) – $CO_2$ uptake (new surface area)* ***{Equation 38}***

Table 18 results ensure that the uptake boundary is respected while providing an uptake value if the boundary is not reached. As a result, the additive $CO_2$ value can be calculated by subtracting the values in Table 18 from Line 37.

Table 19A results do not consider any energy expenditure (and associated $CO_2$ emission) for material preparation – namely, crushing concrete to the desired aggregate size.

| Output (Table 19A - Aggregate, Additive $CO_2$ w/o crushing) | | | | |
|---|---|---|---|---|
| time (year) = 40 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 316.82 | 356.63 | 460.17 | 563.72 |
| Buried | 316.82 | 316.82 | 356.63 | 460.17 |
| Exposed | 316.82 | 316.82 | 316.82 | 356.63 |
| Sheltered | 316.82 | 316.82 | 316.82 | 316.82 |
| Indoors | 316.82 | 316.82 | 316.82 | 316.82 |

Table 19B shows the calculated results for the total additive $CO_2$ in kilograms per tonne of cement based on utilizing EOL concrete as aggregates. Table 19B calculations include consideration for energy expenditure (and associated CO2 emission) for material preparation – namely, crushing concrete to the desired aggregate size.

| Output (Table 19B - Aggregate, Additive $CO_2$ w/crushing) | | | | |
|---|---|---|---|---|
| time (year) = 40 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 318.86 | 358.67 | 462.22 | 565.76 |
| Buried | 318.86 | 318.86 | 358.67 | 462.22 |
| Exposed | 318.86 | 318.86 | 318.86 | 358.67 |
| Sheltered | 318.86 | 318.86 | 318.86 | 318.86 |
| Indoors | 318.86 | 318.86 | 318.86 | 318.86 |

Tables 15C, 16C, 16D, 17C, 18C, 19C and 19D incorporate the uptake error (1.68% per millimeter of penetration error on a 100-year basis) into the date for Tables 15, 16A, 16B, 17, 18, 19A and 19B, respectively.

| Output (Table 15C - $CO_2$ uptake available to reach maximum/$m^3$ concrete w/error) | | | | |
|---|---|---|---|---|
| time (year) = 20 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 126.09 | 130.39 | 131.49 | 132.59 |
| Buried | 121.95 | 128.22 | 130.39 | 131.49 |
| Exposed | 114.12 | 124.00 | 128.22 | 130.39 |
| Sheltered | 97.21 | 110.44 | 117.96 | 124.00 |
| Indoors | 84.09 | 100.29 | 110.44 | 119.94 |

| Output (Table 16C - $CO_2$ uptake per $m^3$, unbound, old surface area w/error) | | | | |
|---|---|---|---|---|
| time (year) = Year 21 to year 40 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 3.62 | 1.84 | 1.39 | 0.93 |
| Buried | 5.34 | 2.74 | 1.84 | 1.39 |
| Exposed | 8.58 | 4.49 | 2.74 | 1.84 |
| Sheltered | 15.59 | 10.11 | 6.99 | 4.49 |
| Indoors | 21.02 | 14.31 | 10.11 | 6.17 |

| Output (Table 16D - $CO_2$ uptake per $m^3$, unbound, new surface area w/error) | | | | |
|---|---|---|---|---|
| time (year) = Year 21 to year 40 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 225.40 | 114.66 | 86.36 | 57.82 |
| Buried | 332.22 | 170.52 | 114.66 | 86.36 |
| Exposed | 534.10 | 279.30 | 170.52 | 114.66 |
| Sheltered | 970.25 | 629.17 | 435.12 | 279.30 |
| Indoors | 1,308.43 | 890.85 | 629.17 | 384.16 |

| Output (Table 17C - total $CO_2$ uptake per $m^3$, max bound w/error) | | | | |
|---|---|---|---|---|
| time (year) = 40 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 134.84 | 120.95 | 91.10 | 60.99 |
| Buried | 134.84 | 134.84 | 120.95 | 91.10 |
| Exposed | 134.84 | 134.84 | 134.84 | 120.95 |
| Sheltered | 134.84 | 134.84 | 134.84 | 134.84 |
| Indoors | 134.84 | 134.84 | 134.84 | 134.84 |

| Output (Table 18C - $CO_2$ uptake per tonne cement, max bound w/error) | | | | |
|---|---|---|---|---|
| time (year) = 40 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 453.99 | 407.22 | 306.72 | 205.35 |
| Buried | 453.99 | 453.99 | 407.22 | 306.72 |
| Exposed | 453.99 | 453.99 | 453.99 | 407.22 |
| Sheltered | 453.99 | 453.99 | 453.99 | 453.99 |
| Indoors | 453.99 | 453.99 | 453.99 | 453.99 |

| Output (Table 19C - Aggregate, Additive $CO_2$ w/o crushing w/error) | | | | |
|---|---|---|---|---|
| time (year) = 40 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 316.82 | 363.59 | 464.09 | 565.46 |
| Buried | 316.82 | 316.82 | 363.59 | 464.09 |
| Exposed | 316.82 | 316.82 | 316.82 | 363.59 |
| Sheltered | 316.82 | 316.82 | 316.82 | 316.82 |
| Indoors | 316.82 | 316.82 | 316.82 | 316.82 |

| Output (Table 19D - Aggregate, Additive $CO_2$ w/crushing w/error) | | | | |
|---|---|---|---|---|
| time (year) = 40 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 318.86 | 365.63 | 466.13 | 567.50 |
| Buried | 318.86 | 318.86 | 365.63 | 466.13 |
| Exposed | 318.86 | 318.86 | 318.86 | 365.63 |
| Sheltered | 318.86 | 318.86 | 318.86 | 318.86 |
| Indoors | 318.86 | 318.86 | 318.86 | 318.86 |

Table 19E shows the calculated results for the percentage error of additive $CO_2$ as the difference between Table 19B and Table 19D. The percent error in Table 19D reflects the full error of additive $CO_2$ emissions rather than just the uptake error.

| Output (Table 19E - Aggregate, Additive $CO_2$ error) | | | | |
|---|---|---|---|---|
| time (year) = 40 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 0.00% | 1.90% | 0.84% | 0.31% |
| Buried | 0.00% | 0.00% | 1.90% | 0.84% |
| Exposed | 0.00% | 0.00% | 0.00% | 1.90% |
| Sheltered | 0.00% | 0.00% | 0.00% | 0.00% |
| Indoors | 0.00% | 0.00% | 0.00% | 0.00% |

### 5.5.1 Aggregate Utilization (time periods 3 through 5)

The previous section showed the model outputs for time periods one and two for the aggregate utilization scenario. Specifically, period one is the first service life as concrete and period two is the same duration but with surface area relative to the aggregate sizing. This section shows the model outputs for the remaining time periods to reach 100 year and associated $CO_2$ uptake during these periods.

Tables 20A through 20D show the calculated results for the same information as Tables 16A through 16D for the next sequential time period. To carry through from the previous example, this represents the $CO_2$ uptake by the material from years 41 through 60 – namely, the 3rd sequential period for a duration equivalent to the initial service life of 20 years.

| Output (Table 20A - $CO_2$ uptake per $m^3$, unbound, old surface area) | | | | |
|---|---|---|---|---|
| | time (year) = | Year 41 to year 60 | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 2.87 | 1.44 | 1.08 | 0.72 |
| Buried | 4.31 | 2.16 | 1.44 | 1.08 |
| Exposed | 7.19 | 3.59 | 2.16 | 1.44 |
| Sheltered | 14.37 | 8.62 | 5.75 | 3.59 |
| Indoors | 21.56 | 12.94 | 8.62 | 5.03 |

| Output (Table 20B - $CO_2$ uptake per m3, unbound, new surface area) | | | | |
|---|---|---|---|---|
| | time (year) = | Year 41 to year 60 | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 96.61 | 48.30 | 36.23 | 24.15 |
| Buried | 144.91 | 72.46 | 48.30 | 36.23 |
| Exposed | 241.52 | 120.76 | 72.46 | 48.30 |
| Sheltered | 483.04 | 289.82 | 193.22 | 120.76 |
| Indoors | 724.56 | 434.74 | 289.82 | 169.06 |

| Output (Table 20C - $CO_2$ uptake per $m^3$, unbound, old surface area w/error) | | | | |
|---|---|---|---|---|
| | time (year) = | Year 41 to year 60 | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 2.78 | 1.41 | 1.06 | 0.71 |
| Buried | 4.09 | 2.10 | 1.41 | 1.06 |
| Exposed | 6.58 | 3.44 | 2.10 | 1.41 |
| Sheltered | 11.96 | 7.76 | 5.36 | 3.44 |
| Indoors | 16.13 | 10.98 | 7.76 | 4.74 |

| Output (Table 20D - $CO_2$ uptake per $m^3$, unbound, new surface area w/error) | | | | |
|---|---|---|---|---|
| | time (year) = | Year 41 to year 60 | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 93.36 | 47.49 | 35.77 | 23.95 |
| Buried | 137.61 | 70.63 | 47.49 | 35.77 |
| Exposed | 221.23 | 115.69 | 70.63 | 47.49 |
| Sheltered | 401.89 | 260.61 | 180.23 | 115.69 |
| Indoors | 541.97 | 369.00 | 260.61 | 159.12 |

Table 21 shows the calculated results for the total $CO_2$ uptake per $m^3$ within the upper boundary of the potential $CO_2$ uptake as per Line 20 in the input table using the information from Tables 20A, 20B, and 17.

| Output (Table 21 - total $CO_2$ uptake per $m^3$, max bound) | | | | |
|---|---|---|---|---|
| | time (year) = | 60 | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 134.84 | 134.84 | 129.56 | 86.38 |
| Buried | 134.84 | 134.84 | 134.84 | 129.56 |
| Exposed | 134.84 | 134.84 | 134.84 | 134.84 |
| Sheltered | 134.84 | 134.84 | 134.84 | 134.84 |
| Indoors | 134.84 | 134.84 | 134.84 | 134.84 |

Tables 21C incorporates the uptake error (1.68% per millimeter of penetration error on a 100-year basis) into the date for Tables 21. Error adjustments can be made in Table B1 but set to 100-year basis as default. Error drops to zero once maximum uptake has been reached.

| Output (Table 21C - total $CO_2$ uptake per $m^3$, max bound w/error) | | | | |
|---|---|---|---|---|
| | time (year) = | 60 | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 134.84 | 134.84 | 127.93 | 85.65 |
| Buried | 134.84 | 134.84 | 134.84 | 127.93 |
| Exposed | 134.84 | 134.84 | 134.84 | 134.84 |
| Sheltered | 134.84 | 134.84 | 134.84 | 134.84 |
| Indoors | 134.84 | 134.84 | 134.84 | 134.84 |

Tables 22 through 23E show the calculated results for the same information as Tables 18 through 19E for the next sequential time period.

| Output (Table 22 - $CO_2$ uptake per tonne cement, max bound) | | | | |
|---|---|---|---|---|
| time (year) = 60 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 453.99 | 453.99 | 436.25 | 290.83 |
| Buried | 453.99 | 453.99 | 453.99 | 436.25 |
| Exposed | 453.99 | 453.99 | 453.99 | 453.99 |
| Sheltered | 453.99 | 453.99 | 453.99 | 453.99 |
| Indoors | 453.99 | 453.99 | 453.99 | 453.99 |

| Output (Table 22C - $CO_2$ uptake per tonne cement, max bound w/error) | | | | |
|---|---|---|---|---|
| time (year) = 60 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 453.99 | 453.99 | 430.75 | 288.39 |
| Buried | 453.99 | 453.99 | 453.99 | 430.75 |
| Exposed | 453.99 | 453.99 | 453.99 | 453.99 |
| Sheltered | 453.99 | 453.99 | 453.99 | 453.99 |
| Indoors | 453.99 | 453.99 | 453.99 | 453.99 |

| Output (Table 23A - Aggregate, Additive $CO_2$ w/o crushing) | | | | |
|---|---|---|---|---|
| time (year) = 60 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 316.82 | 316.82 | 334.56 | 479.98 |
| Buried | 316.82 | 316.82 | 316.82 | 334.56 |
| Exposed | 316.82 | 316.82 | 316.82 | 316.82 |
| Sheltered | 316.82 | 316.82 | 316.82 | 316.82 |
| Indoors | 316.82 | 316.82 | 316.82 | 316.82 |

| Output (Table 23B - Aggregate, Additive $CO_2$ w/crushing) | | | | |
|---|---|---|---|---|
| time (year) = 60 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 318.86 | 318.86 | 336.61 | 482.02 |
| Buried | 318.86 | 318.86 | 318.86 | 336.61 |
| Exposed | 318.86 | 318.86 | 318.86 | 318.86 |
| Sheltered | 318.86 | 318.86 | 318.86 | 318.86 |
| Indoors | 318.86 | 318.86 | 318.86 | 318.86 |

| Output (Table 23C - Aggregate, Additive $CO_2$ w/o crushing w/error) | | | | |
|---|---|---|---|---|
| time (year) = 60 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 316.82 | 316.82 | 340.06 | 482.42 |
| Buried | 316.82 | 316.82 | 316.82 | 340.06 |
| Exposed | 316.82 | 316.82 | 316.82 | 316.82 |
| Sheltered | 316.82 | 316.82 | 316.82 | 316.82 |
| Indoors | 316.82 | 316.82 | 316.82 | 316.82 |

| Output (Table 23D - Aggregate, Additive $CO_2$ w/crushing w/error) | | | | |
|---|---|---|---|---|
| time (year) = 60 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 318.86 | 318.86 | 342.11 | 484.47 |
| Buried | 318.86 | 318.86 | 318.86 | 342.11 |
| Exposed | 318.86 | 318.86 | 318.86 | 318.86 |
| Sheltered | 318.86 | 318.86 | 318.86 | 318.86 |
| Indoors | 318.86 | 318.86 | 318.86 | 318.86 |

| Output (Table 23E - Aggregate, Additive $CO_2$ error) | | | | |
|---|---|---|---|---|
| time (year) = 60 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 0.00% | 0.00% | 1.61% | 0.50% |
| Buried | 0.00% | 0.00% | 0.00% | 1.61% |
| Exposed | 0.00% | 0.00% | 0.00% | 0.00% |
| Sheltered | 0.00% | 0.00% | 0.00% | 0.00% |
| Indoors | 0.00% | 0.00% | 0.00% | 0.00% |

Tables 24A through 27E show the calculated results for the same information as Tables 20A through 23E for the next sequential time period. To carry through the previous example, this represents the $CO_2$ uptake by the material from years 61 through 80 – namely, the 4th sequential period for a duration equivalent to the initial service life of 20 years.

| Output (Table 24A - $CO_2$ uptake per $m^3$, unbound, old surface area) | | | | |
|---|---|---|---|---|
| | time (year) = | Year 61 to year 80 | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 2.42 | 1.21 | 0.91 | 0.61 |
| Buried | 3.64 | 1.82 | 1.21 | 0.91 |
| Exposed | 6.06 | 3.03 | 1.82 | 1.21 |
| Sheltered | 12.12 | 7.27 | 4.85 | 3.03 |
| Indoors | 18.18 | 10.91 | 7.27 | 4.24 |

| Output (Table 24B - $CO_2$ uptake per $m^3$, unbound, new surface area) | | | | |
|---|---|---|---|---|
| | time (year) = | Year 61 to year 80 | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 74.13 | 37.06 | 27.80 | 18.53 |
| Buried | 111.19 | 55.60 | 37.06 | 27.80 |
| Exposed | 185.32 | 92.66 | 55.60 | 37.06 |
| Sheltered | 370.65 | 222.39 | 148.26 | 92.66 |
| Indoors | 555.97 | 333.58 | 222.39 | 129.73 |

| Output (Table 24C - $CO_2$ uptake per $m^3$, unbound, old surface area w/error) | | | | |
|---|---|---|---|---|
| | time (year) = | Year 61 to year 80 | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 2.42 | 1.21 | 0.91 | 0.61 |
| Buried | 3.64 | 1.82 | 1.21 | 0.91 |
| Exposed | 6.06 | 3.03 | 1.82 | 1.21 |
| Sheltered | 12.12 | 7.27 | 4.85 | 3.03 |
| Indoors | 18.18 | 10.91 | 7.27 | 4.24 |

| Output (Table 24D - $CO_2$ uptake per $m^3$, unbound, new surface area w/error) | | | | |
|---|---|---|---|---|
| time (year) = Year 41 to year 60 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 71.64 | 37.06 | 27.80 | 18.53 |
| Buried | 111.19 | 55.60 | 37.06 | 27.80 |
| Exposed | 185.32 | 92.66 | 55.60 | 37.06 |
| Sheltered | 370.65 | 222.39 | 148.26 | 92.66 |
| Indoors | 555.97 | 333.58 | 222.39 | 129.73 |

| Output (Table 25 - total $CO_2$ uptake per $m^3$, max bound) | | | | |
|---|---|---|---|---|
| time (year) = 80 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 134.84 | 134.84 | 134.84 | 105.52 |
| Buried | 134.84 | 134.84 | 134.84 | 134.84 |
| Exposed | 134.84 | 134.84 | 134.84 | 134.84 |
| Sheltered | 134.84 | 134.84 | 134.84 | 134.84 |
| Indoors | 134.84 | 134.84 | 134.84 | 134.84 |

| Output (Table 25C - total $CO_2$ uptake per $m^3$, max bound w/error) | | | | |
|---|---|---|---|---|
| time (year) = 80 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 134.84 | 134.84 | 134.84 | 104.79 |
| Buried | 134.84 | 134.84 | 134.84 | 134.84 |
| Exposed | 134.84 | 134.84 | 134.84 | 134.84 |
| Sheltered | 134.84 | 134.84 | 134.84 | 134.84 |
| Indoors | 134.84 | 134.84 | 134.84 | 134.84 |

| Output (Table 26 - $CO_2$ uptake per tonne cement, max bound) | | | | |
|---|---|---|---|---|
| time (year) = 80 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 453.99 | 453.99 | 453.99 | 355.27 |
| Buried | 453.99 | 453.99 | 453.99 | 453.99 |
| Exposed | 453.99 | 453.99 | 453.99 | 453.99 |
| Sheltered | 453.99 | 453.99 | 453.99 | 453.99 |
| Indoors | 453.99 | 453.99 | 453.99 | 453.99 |

| Output (Table 26C - $CO_2$ uptake per tonne cement, max bound w/error) | | | | |
|---|---|---|---|---|
| time (year) = 80 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 453.99 | 453.99 | 453.99 | 352.83 |
| Buried | 453.99 | 453.99 | 453.99 | 453.99 |
| Exposed | 453.99 | 453.99 | 453.99 | 453.99 |
| Sheltered | 453.99 | 453.99 | 453.99 | 453.99 |
| Indoors | 453.99 | 453.99 | 453.99 | 453.99 |

| Output (Table 27A - Aggregate, Additive $CO_2$ w/o crushing) | | | | |
|---|---|---|---|---|
| time (year) = 80 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 316.82 | 316.82 | 316.82 | 415.54 |
| Buried | 316.82 | 316.82 | 316.82 | 316.82 |
| Exposed | 316.82 | 316.82 | 316.82 | 316.82 |
| Sheltered | 316.82 | 316.82 | 316.82 | 316.82 |
| Indoors | 316.82 | 316.82 | 316.82 | 316.82 |

| Output (Table 27B - Aggregate, Additive $CO_2$ w/crushing) | | | | |
|---|---|---|---|---|
| time (year) = 80 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 318.86 | 318.86 | 318.86 | 417.59 |
| Buried | 318.86 | 318.86 | 318.86 | 318.86 |
| Exposed | 318.86 | 318.86 | 318.86 | 318.86 |
| Sheltered | 318.86 | 318.86 | 318.86 | 318.86 |
| Indoors | 318.86 | 318.86 | 318.86 | 318.86 |

| Output (Table 27C - Aggregate, Additive $CO_2$ w/o crushing w/error) | | | | |
|---|---|---|---|---|
| time (year) = 80 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 316.82 | 316.82 | 316.82 | 417.98 |
| Buried | 316.82 | 316.82 | 316.82 | 316.82 |
| Exposed | 316.82 | 316.82 | 316.82 | 316.82 |
| Sheltered | 316.82 | 316.82 | 316.82 | 316.82 |
| Indoors | 316.82 | 316.82 | 316.82 | 316.82 |

| Output (Table 27D - Aggregate, Additive $CO_2$ w/crushing w/error) | | | | |
|---|---|---|---|---|
| time (year) = 80 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 318.86 | 318.86 | 318.86 | 420.03 |
| Buried | 318.86 | 318.86 | 318.86 | 318.86 |
| Exposed | 318.86 | 318.86 | 318.86 | 318.86 |
| Sheltered | 318.86 | 318.86 | 318.86 | 318.86 |
| Indoors | 318.86 | 318.86 | 318.86 | 318.86 |

| Output (Table 27E - Aggregate, Additive $CO_2$ error) | | | | |
|---|---|---|---|---|
| time (year) = 80 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 0.00% | 0.00% | 0.00% | 0.58% |
| Buried | 0.00% | 0.00% | 0.00% | 0.00% |
| Exposed | 0.00% | 0.00% | 0.00% | 0.00% |
| Sheltered | 0.00% | 0.00% | 0.00% | 0.00% |
| Indoors | 0.00% | 0.00% | 0.00% | 0.00% |

Tables 28A through 31E show the calculated results for the same information as Tables 24A through 27E for the next sequential time period. To carry through the previous example, this represents the $CO_2$ uptake by the material from years 81 through 100 – namely, the 5$^{th}$ sequential period for a duration equivalent to the initial service life of 20 years.

| Output (Table 28A - $CO_2$ uptake per $m^3$, unbound, old surface area) | | | | |
|---|---|---|---|---|
| time (year) = Year 81 to year 100 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 2.14 | 1.07 | 0.80 | 0.53 |
| Buried | 3.20 | 1.60 | 1.07 | 0.80 |
| Exposed | 5.34 | 2.67 | 1.60 | 1.07 |
| Sheltered | 10.68 | 6.41 | 4.27 | 2.67 |
| Indoors | 16.01 | 9.61 | 6.41 | 3.74 |

| Output (Table 28B - $CO_2$ uptake per $m^3$, unbound, new surface area) | | | | |
|---|---|---|---|---|
| | time (year) = | Year 81 to year 100 | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 62.49 | 31.25 | 23.44 | 15.62 |
| Buried | 93.74 | 46.87 | 31.25 | 23.44 |
| Exposed | 156.24 | 78.12 | 46.87 | 31.25 |
| Sheltered | 312.47 | 187.48 | 124.99 | 78.12 |
| Indoors | 468.71 | 281.22 | 187.48 | 109.37 |

| Output (Table 28C - $CO_2$ uptake per $m^3$, unbound, old surface area w/error) | | | | |
|---|---|---|---|---|
| | time (year) = | Year 81 to year 100 | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 2.06 | 1.05 | 0.79 | 0.53 |
| Buried | 3.04 | 1.56 | 1.05 | 0.79 |
| Exposed | 4.89 | 2.56 | 1.56 | 1.05 |
| Sheltered | 8.88 | 5.76 | 3.98 | 2.56 |
| Indoors | 11.98 | 8.16 | 5.76 | 3.52 |

| Output (Table 28D - $CO_2$ uptake per $m^3$, unbound, new surface area w/error) | | | | |
|---|---|---|---|---|
| | time (year) = | Year 81 to year 100 | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 60.39 | 30.72 | 23.14 | 15.49 |
| Buried | 89.02 | 45.69 | 30.72 | 23.14 |
| Exposed | 143.11 | 74.84 | 45.69 | 30.72 |
| Sheltered | 259.98 | 168.58 | 116.59 | 74.84 |
| Indoors | 350.59 | 238.70 | 168.58 | 102.93 |

| Output (Table 29 - total $CO_2$ uptake per $m^3$, max bound) | | | | |
|---|---|---|---|---|
| | time (year) = | 100 | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 134.84 | 134.84 | 134.84 | 121.67 |
| Buried | 134.84 | 134.84 | 134.84 | 134.84 |
| Exposed | 134.84 | 134.84 | 134.84 | 134.84 |
| Sheltered | 134.84 | 134.84 | 134.84 | 134.84 |
| Indoors | 134.84 | 134.84 | 134.84 | 134.84 |

| Output (Table 29C - total $CO_2$ uptake per $m^3$, max bound w/error) | | | | |
|---|---|---|---|---|
| time (year) = 100 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 134.84 | 134.84 | 134.84 | 120.81 |
| Buried | 134.84 | 134.84 | 134.84 | 134.84 |
| Exposed | 134.84 | 134.84 | 134.84 | 134.84 |
| Sheltered | 134.84 | 134.84 | 134.84 | 134.84 |
| Indoors | 134.84 | 134.84 | 134.84 | 134.84 |

| Output (Table 30 - $CO_2$ uptake per tonne cement, max bound) | | | | |
|---|---|---|---|---|
| time (year) = 100 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 453.99 | 453.99 | 453.99 | 409.67 |
| Buried | 453.99 | 453.99 | 453.99 | 453.99 |
| Exposed | 453.99 | 453.99 | 453.99 | 453.99 |
| Sheltered | 453.99 | 453.99 | 453.99 | 453.99 |
| Indoors | 453.99 | 453.99 | 453.99 | 453.99 |

| Output (Table 30C - $CO_2$ uptake per tonne cement, max bound w/error) | | | | |
|---|---|---|---|---|
| time (year) = 100 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 453.99 | 453.99 | 453.99 | 406.77 |
| Buried | 453.99 | 453.99 | 453.99 | 453.99 |
| Exposed | 453.99 | 453.99 | 453.99 | 453.99 |
| Sheltered | 453.99 | 453.99 | 453.99 | 453.99 |
| Indoors | 453.99 | 453.99 | 453.99 | 453.99 |

| Output (Table 31A - Aggregate, Additive $CO_2$ w/o crushing) | | | | |
|---|---|---|---|---|
| time (year) = 100 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 316.82 | 316.82 | 316.82 | 361.14 |
| Buried | 316.82 | 316.82 | 316.82 | 316.82 |
| Exposed | 316.82 | 316.82 | 316.82 | 316.82 |
| Sheltered | 316.82 | 316.82 | 316.82 | 316.82 |
| Indoors | 316.82 | 316.82 | 316.82 | 316.82 |

| Output (Table 31B - Aggregate, Additive $CO_2$ w/crushing) | | | | |
|---|---|---|---|---|
| time (year) = 100 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 318.86 | 318.86 | 318.86 | 363.18 |
| Buried | 318.86 | 318.86 | 318.86 | 318.86 |
| Exposed | 318.86 | 318.86 | 318.86 | 318.86 |
| Sheltered | 318.86 | 318.86 | 318.86 | 318.86 |
| Indoors | 318.86 | 318.86 | 318.86 | 318.86 |

| Output (Table 31C - Aggregate, Additive $CO_2$ w/o crushing w/error) | | | | |
|---|---|---|---|---|
| time (year) = 100 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 316.82 | 316.82 | 316.82 | 364.04 |
| Buried | 316.82 | 316.82 | 316.82 | 316.82 |
| Exposed | 316.82 | 316.82 | 316.82 | 316.82 |
| Sheltered | 316.82 | 316.82 | 316.82 | 316.82 |
| Indoors | 316.82 | 316.82 | 316.82 | 316.82 |

| Output (Table 31D - Aggregate, Additive $CO_2$ w/crushing w/error) | | | | |
|---|---|---|---|---|
| time (year) = 100 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 318.86 | 318.86 | 318.86 | 366.08 |
| Buried | 318.86 | 318.86 | 318.86 | 318.86 |
| Exposed | 318.86 | 318.86 | 318.86 | 318.86 |
| Sheltered | 318.86 | 318.86 | 318.86 | 318.86 |
| Indoors | 318.86 | 318.86 | 318.86 | 318.86 |

| Output (Table 31E - Aggregate, Additive $CO_2$ error) | | | | |
|---|---|---|---|---|
| time (year) = 100 | | | | |
| | Compressive Strength | | | |
| | <15 MPa | 15-20 MPa | 25-30 MPa | > 35 MPa |
| Wet | 0.00% | 0.00% | 0.00% | 0.79% |
| Buried | 0.00% | 0.00% | 0.00% | 0.00% |
| Exposed | 0.00% | 0.00% | 0.00% | 0.00% |
| Sheltered | 0.00% | 0.00% | 0.00% | 0.00% |
| Indoors | 0.00% | 0.00% | 0.00% | 0.00% |

The model tables show data for five consecutive service lives. This can be extended to captured additional service lives depending on the interest of the timeline to be evaluated.

## 5.6 Aggregate Utilization Condition

Aggregate utilization throughout this chapter is considered as 'wet' with the initial service life also being 'wet'. The model allows for the evaluation of any combination of initial service life and end of life use – namely; wet (immersed water); buried (below grade application); exposed (exterior application above grade and exposed to precipitation); sheltered (not directly exposed to exterior or interior conditions); and indoor (interior applications).

The primary uses of concrete in 'wet' or 'buried' conditions are excluded in the practical evaluation in Chapter 7 with the understanding that concrete applications in environments that are either submerged in water or buried underground will have specific design criteria with respect to strength and service life that may not warrant removal and reprocessing. Additionally, the extraction of submerged or buried material is less likely for reuse.

Secondary use of EOL concrete is also restricted to only exposed or buried application – specifically, above ground where gravel or crushed stone would otherwise be used or subgrade application such as road base. It is not expected that the EOL concrete will be used for indoor or sheltered applications (in homes or building) or wet conditions where water quality aspects may dictate aggregate specifications.

These applications, however, are not excluded from the model as the evolution of technology and construction techniques may allow for deconstruction of all concrete for reuse regardless of application.

## 5.7 Model Output & Conclusion

The model output captures the information of the Gross $CO_2$ emissions in kilograms $CO_2$ per tonne of cement (Line 37 from input model) as the initial production number. The Raw Material and Clinker 2nd Production values are obtained from Tables 10A and 14B, respectively. The $CO_2$ uptake values are obtained from Table 3, 18, 22, 26, and 30.

A sample output table (Table 5.2) is presented without error calculation. The totals at the bottom of the table are colour coordinated to show the best selection of EOL use based on cumulative additive $CO_2$ emissions over a 100-year period. The output presented in Table 5.2 shows that the EOL use as Aggregate results in the lowest additive $CO_2$ emissions for the specific scenario tested in this chapter with Raw Material and Clinker substitution as the second and third best options, respectively.

Appendix C includes results in the format show in Table 5.2 and Figure 5.1 below for all practical application scenarios including Sheltered, Indoor, and Exposed initial applications with EOL utilization as Buried and Exposed. The model summarized in Appendix C highlights that, similar to the results shown in Table 5.2, Raw Material substitution reduces additive $CO_2$ emissions from cement manufacturing greater than Clinker Substitution when material circularity is respected.

The individual streams calculated in the model show the benefit of material circularity of raw material and clinker substitution in reducing additive $CO_2$ emissions as well Carbon Capture and Utilization (CCU) benefit with EOL concrete utilized in aggregate application. This model structure, specifically the evaluation of individual streams of application, allows for the empirical evaluation of two critical parts of the Carbon Hierarchy presented Chapter 3 – namely, Stretching and Sequestering (including Uptake). Chapter 6 continues the evaluation of the Carbon Hierarchy with the quantification of Life Extension, Process Optimization, and Industrial Symbiosis.

| *Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*<br>*Jurisdiction: Canada; Service Life: 20 years* | **Primary**<br>**Wet** | **Secondary**<br>**Wet** | **Strength**<br>**<15 MPa** |
|---|---|---|---|
| **Substituion Type** | **Raw Material** | **Clinker** | **Aggregates** |
| 1st Production | 771 | 771 | 771 |
| CO2 Uptake Year 0 to 20 | -30 | -30 | -30 |
| 2nd Production | 704 | 767 | 771 |
| CO2 Uptake for Year 21 to 40 (2nd Production) | -30 | -30 | -30 |
| CO2 Uptake for Year 21 to 40 (1st Production Aggregates) | | | -424 |
| 3rd Production | 704 | 767 | 771 |
| CO2 Uptake for Year 41 to 60 (3rd Production) | -30 | -30 | -30 |
| CO2 Uptake for Year 41 to 60 (2nd Production Aggregates) | | | -424 |
| CO2 Uptake for Year 41 to 60 (1st Production Aggregates) | | | 0 |
| 4th Production | 704 | 767 | 771 |
| CO2 Uptake for Year 61 to 80 (4th Production) | -30 | -30 | -30 |
| CO2 Uptake for Year 61 to 80 (3rd Production Aggregates) | | | -424 |
| CO2 Uptake for Year 61 to 80 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 61 to 80 (1st Production Aggregates) | | | 0 |
| 5th Production | 704 | 767 | 771 |
| CO2 Uptake for Year 81 to 100 (4th Production) | -30 | -30 | -30 |
| CO2 Uptake for Year 81 to 100 (4th Production Aggregates) | | | -424 |
| CO2 Uptake for Year 81 to 100 (3rd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (1st Production Aggregates) | | | 0 |
| Total Additive CO2 after 100 years | 3435 | 3688 | 2008 |

| | | | |
|---|---|---|---|
| Additive CO2 After 20 years | 740.36 | 740.36 | 740.36 |
| Additive CO2 After 40 years | 1,414.04 | 1,477.34 | 1,059.22 |
| Additive CO2 After 60 years | 2,087.72 | 2,214.32 | 1,378.09 |
| Additive CO2 After 80 years | 2,761.40 | 2,951.30 | 1,696.95 |
| Additive CO2 After 100 years | 3,435.08 | 3,688.28 | 2,015.82 |

*Table 5.2: Model Output Table*

*Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*
*Jurisdiction: Canada; Service Life: 20 years*

| Primary | Secondary | Strength |
|---|---|---|
| Wet | Wet | <15 MPa |

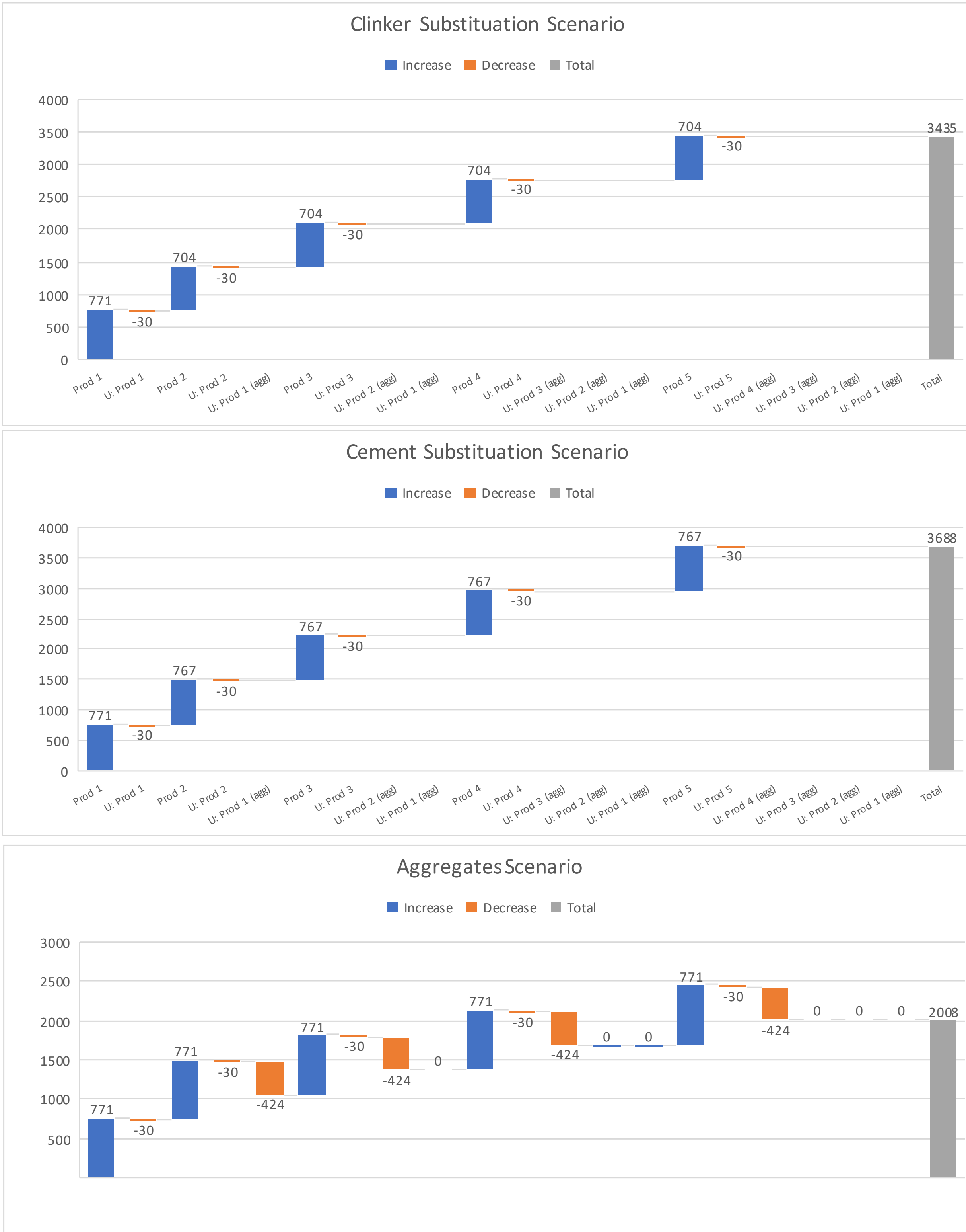


*Figure 5.1: Model Output Table*

# Chapter 6

# Generalized Application of the Carbon Hierarchy

The following chapter presents an assessment of the Carbon Hierarchy as presented in Chapter 3 using the unique model developed to quantify material circularity and $CO_2$ uptake in Chapter 4. The goal is to determine whether the Carbon Hierarchy is an effective model for decision making – primarily, will adhering to the Carbon Hierarchy result in a reduction of carbon dioxide output in the order presented in the hierarchy. The following hypothesis is tested in this chapter within a generalized application: *If a successive stage hierarchy for carbon mitigation and material circularity is created it would ensure rational carbon reduction and resource conservation decision-making in the cement industry.*

## 6.1 Overview

The following assessment evaluates the potential impact of cement manufacturing in Canada with respect to carbon dioxide uptake during the primary service life with comparison to secondary use options – specifically; (1) returning crushed concrete for clinker manufacturing (as raw material substitute); (2) returning crushed concrete for cement manufacturing (as clinker substitute): or (3) using crushed concrete for aggregate application. The assessment tool used in this chapter is based on the model developed and demonstrated in Chapters 4 and 5, respectively.

The Carbon Hierarchy as presented in Chapter 3 (Figure 6.1 below) is evaluated for the cement industry in a Canadian context to determine whether it is an effective model for decision making – ie. will adhering to the Carbon Hierarchy result in a reduction of carbon output in the order presented in the hierarchy? The following hypothesis is tested in this chapter within a generalized application: *If a successive stage hierarchy for carbon mitigation and material circularity is created it would ensure rational carbon reduction and resource conservation decision-making in the cement industry.*

Ultimately, the actions at the top of the hierarchy - Life Extension and Process Optimization - should result in carbon emissions reduction (more accurately, less additive carbon output) that do not interfere with actions further down the hierarchy. This hypothesis will be tested by applying various scenarios to the Canadian cement industry. An important part of the hypothesis is that the Carbon Hierarchy cannot be used independently of the fundamental principles of resource conservation. In other words, carbon capture utilization and storage (if yielding reduced carbon emissions) is ultimately reliant on perpetual resources and sinks.

If the Carbon Hierarchy is accurate then the following can be shown to be empirically accurate.

1) Avoidance of carbon dioxide emissions through the reduction or decarbonation of thermal/electrical energy will yield results that are in line with the extension of service life through the production of better materials or repairs. Therefore, improving operational efficiency but keeping service life unchanged would be equivalent to extending the service life of material where the operational efficiency is not improved.
2) Carbon dioxide emission reductions associated with material circularity depends largely on the application type and concrete strength as presented in the model structures of Chapter 4.
3) Stretching[1] is a critical element of the carbon hierarchy and, with the unique carbonation process of concrete during its service life, can significantly reduce carbon dioxide emissions from cement manufacturing.

If the Carbon Hierarchy can accurately order carbon reduction opportunities while ensuring material conservation is respected, this will provide a clear structure for cement manufacturers and policymakers to invest in technologies and processes to reach a carbon neutral cement industry. Secondly, it will answer a critical question of the amount of Carbon Capture Utilization and Storage (CCUS) the cement industry will need to invest in to offset any remaining emissions

[1] Defined in Section 3.3.2 in Chapter 3. Stretching is a novel concept that includes material circularity and industrial symbiosis. Stretching is fundamentally different from Avoidance as the reduction is only related to the secondary beneficial use of the material for which carbon dioxide was released to create in the first place. It is important to note that Stretching is a partial reduction while Avoidance is a complete reduction.

after Avoidance and Stretching are exhausted. Finally, the Carbon Hierarchy is purposely broad enough that it would allow for adoption regardless of industry or policy maturity in any given jurisdiction.

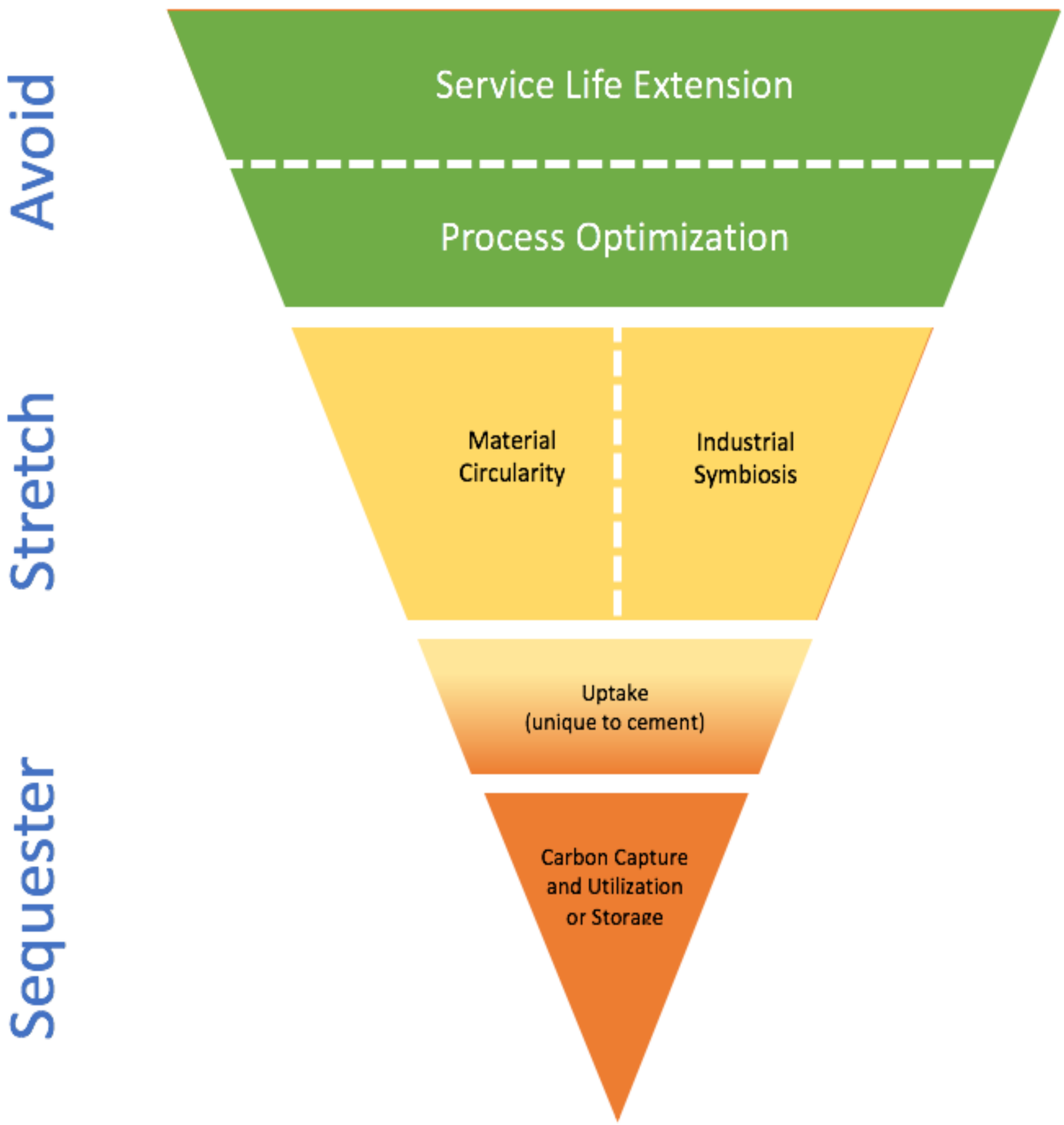


Figure 6.1: Proposed Carbon Hierarchy

## 6.2 Scope of the Assessment

Carbon dioxide emissions throughout this chapter are evaluated in the form of tonnes of $CO_2$ per tonne of cement per service year (the acronym CIPS will be used from here on in for simplicity – this is borrowing from a well-known concept of MIPS, Material Input Per unit of Service (Liedtke, 2012). The purpose of this metric is to ensure that extending service life of material, including through partial repair or replacement, can be quantified. All values are assessed over a total of 100 years with three service life scenarios – namely, 20 years; 33.3 years, and 50 years. Service life can range from 4 years to 90 years with an average of 35 years in China up to 70 years in Europe (Xi et al., 2016).

Each scenario considers the production cycle to match the service life scenarios. A service life of 20 years will result in the production of cement at year 0, 20, 40, 60, and 80 to provide a service for 100 years. Similarly, a service life of 33.3 years will result in the production of cement at year 0, 33.3, and 66.6 while a service life of 50 years will result in the production of cement at year 0 and 50 to achieve the same overall service period of 100 years. The time periods selected allow for reasonable coverage of potential service life timeframes while ensuring the full service life periods can be assessed within the 100-year period.

The following scenarios are assessed to test the Carbon Hierarchy hypothesis (all assessments are conducted on a total of 100-year basis):

a. Avoidance
    i. Life Extension
        1. 20-year (baseline)
        2. Design - 33.3 year (with increase cement content)
        3. Design - 50 year (with increased cement content)
        4. Repair
    ii. Process Optimization
        1. Thermal Energy Decarbonization
        2. Complete Energy Decarbonization
        3. Limestone Addition up to 35% EU Standard
b. Stretching
    i. Industrial Symbiosis
        1. Blast-Furnace Slag up to 80%
    ii. Material Circularity
        1. Raw Material Substitution
        2. Clinker Substitution
c. Sequestration
    i. Carbon Capture & Utilization
        1. Aggregates from end-of-life (EOL) Concrete

The baseline scenario considers the production of one tonne of cement to have an impact of 771 kg of $CO_2$ as per the baseline model output (Chapter 5). This value when converted for a 20-year service life will result in total emissions of 3855 kg $CO_2$ (when 771 kg $CO_2$/t cement is multiplied by five iterations of production at year 0, 20, 40, 60, and 80). The overall service period of 100 years results in a value of 38.55 kg $CO_2$ per tonne of cement per service year (shown in Table 6.1 below) as *Baseline (20 years)* rounded to a value of 39.

## 6.3 Avoidance

### 6.3.1 Life Extension

The primary assessment is to evaluate the extension of service life. Various scenarios are evaluated by increasing the need for cement by 10% in concrete from 10% increase to 50% increase for service life increments of 33.3 and 50 years. A third set of scenarios is where the cement content in concrete remains the same but either 25% or 50% of the material requires replacement at each production iteration (i.e. every 20 years). Increase in cement addition for concrete strength is used as a proxy for longevity. It is clear that longevity is not simply a function of strength, but this is based on the expectation that the only logical reason to increase cement concrete and produce high strength concrete where structural strength does not demand it explicitly is to increase service life. This assumption is used not as a point of debate for concrete mix design and application but rather to evaluate the sensitivity of service life extension relative to cement content.

The results, as shown in Tables 6.1 and 6.2 and Figure 6.2, demonstrate a somewhat intuitive outcome that the increasing service life with the least amount of additional cement addition will produce a lower CIPS value. The calculation for CIPS for an Extended Service Life scenario in Tables 1 and 2 is:

$$CIPS = Production\ (kg\ CO_2/t\ cement\ ) * (1 + \%\ increase\ in\ cement) * \frac{100}{service\ life\ (years)}$$

| | Baseline (20 years) | +10% cement, 33.3 year service life | +20% cement, 33.3 year service life | +30% cement, 33.3 year service life | +40% cement, 33.3 year service life | +50% cement, 33.3 year service life | +10% cement, 50 year service life | +20% cement, 50 year service life | +30% cement, 50 year service life | +40% cement, 50 year service life | +50% cement, 50 year service life |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Production (kg CO2/t cement) | 771 | 848 | 925 | 1002 | 1079 | 1157 | 848 | 925 | 1002 | 1079 | 1157 |
| Total (kg CO2 over 100 years) | 3855 | 2544 | 2776 | 3007 | 3238 | 3470 | 1696 | 1850 | 2005 | 2159 | 2313 |
| CIPS (kg CO2 per tonne cement/year) | 39 | 25 | 28 | 30 | 32 | 35 | 17 | 19 | 20 | 22 | 23 |

*Table 6.1: Avoidance - Extended Service Life (Design)*

Table 6.2 calculates the CIPS value for repair or replacement of 25% and 50% of the cement (and in turn, concrete) at the end of each service life.

| | Baseline (20 years) | +25% repair per service period | +50% repair per service period |
|---|---|---|---|
| Production (kg CO2/t cement) | 771 | 771 | 771 |
| Total (kg CO2 over 100 years) | 3855 | 1542 | 2313 |
| CIPS (kg CO2 per tonne cement/year) | 39 | 15 | 23 |

*Table 6.2: Avoidance - Extended Service Life (Repair)*

The results from Extended Service Life show that CIPS is reduced to between 15 to 35 based on the scenario evaluated. These are, of course, hypothetical scenarios but the linearity of the calculations highlight that extended service life can have a proportionally significant reduction in the CIPS value.

### 6.3.2 Process Optimization

Process Optimization is calculated and presented in Figures 6.3 and 6.4. Figure 6.3 shows the outcome of a sensitivity analysis for decarbonizing both the electrical and thermal energy for Canadian operations. Decarbonization can be used interchangeably for process efficiency in the Process Optimization model as the values are a product of the energy input and $CO_2$ emissions per unit of energy input. However, from a technology standpoint, efficiency and decarbonization are not equivalent. The reduction of electrical energy can be achieved through waste heat recovery (WHR) or combined heat and power systems (CHP). Thermal energy requirements, however, are tied to the need for a specific energy input for the chemical process of clinker manufacturing – as such, decarbonization may be a more realistic process change.

As expected, based on the model input, the vast majority of the $CO_2$ emissions from Canadian cement operations are related to calcination and thermal energy emissions. Although the data shows that there is a small decrease with the decarbonization of electrical energy. However, this is a negligible amount when calculated as a CIPS value due to the low $CO_2$ emissions from electrical generation of 145 grams $CO_2$ per kilowatt hour, four-fold lower than the G20 average (Climate Transparency, 2017).

Thermal energy, therefore, has a significant impact on CIPS, as shown in Figure 6.3, resulting in a CIPS value between 24 and 35 based on the percentage of decarbonization (electrical energy does reduce CIPS to 23 when 100% decarbonation of both electrical and thermal energy is assessed).

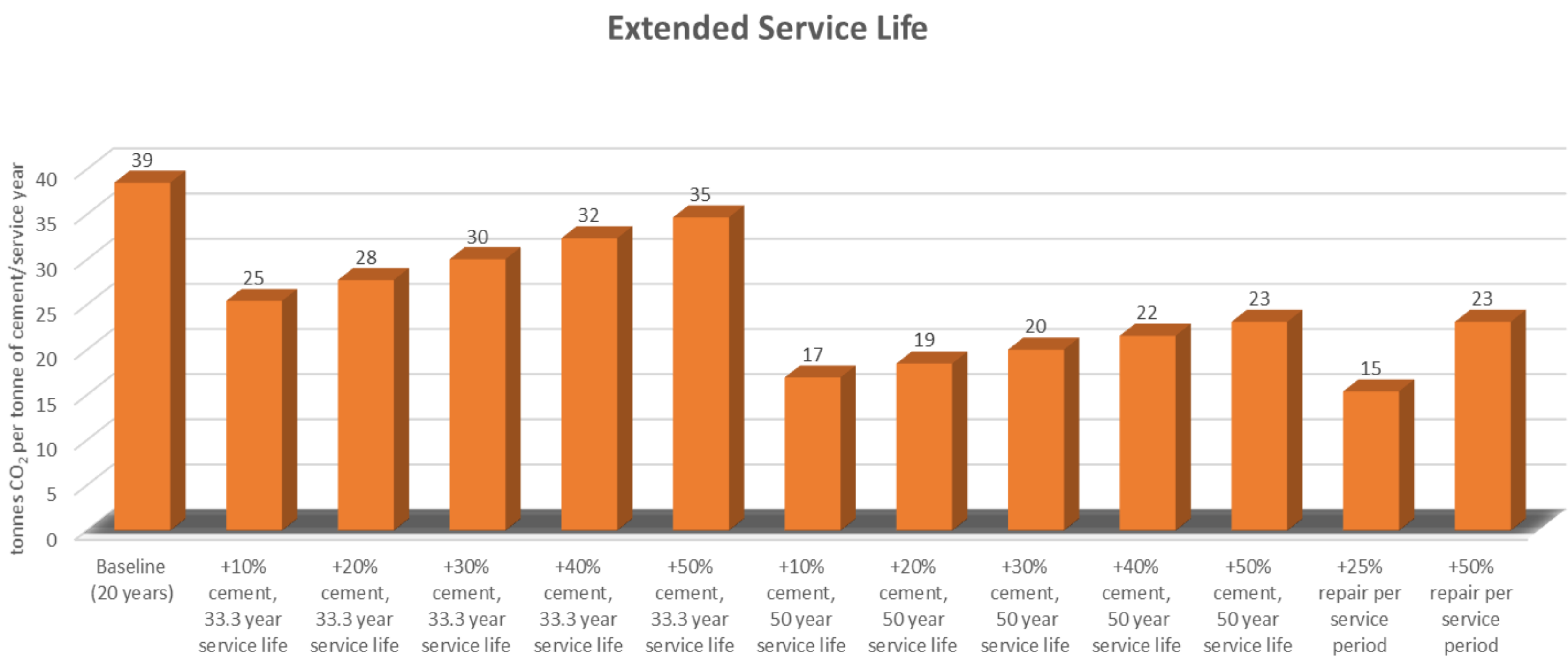


*Figure 6.2: Extended Service Life (Design & Repair)*

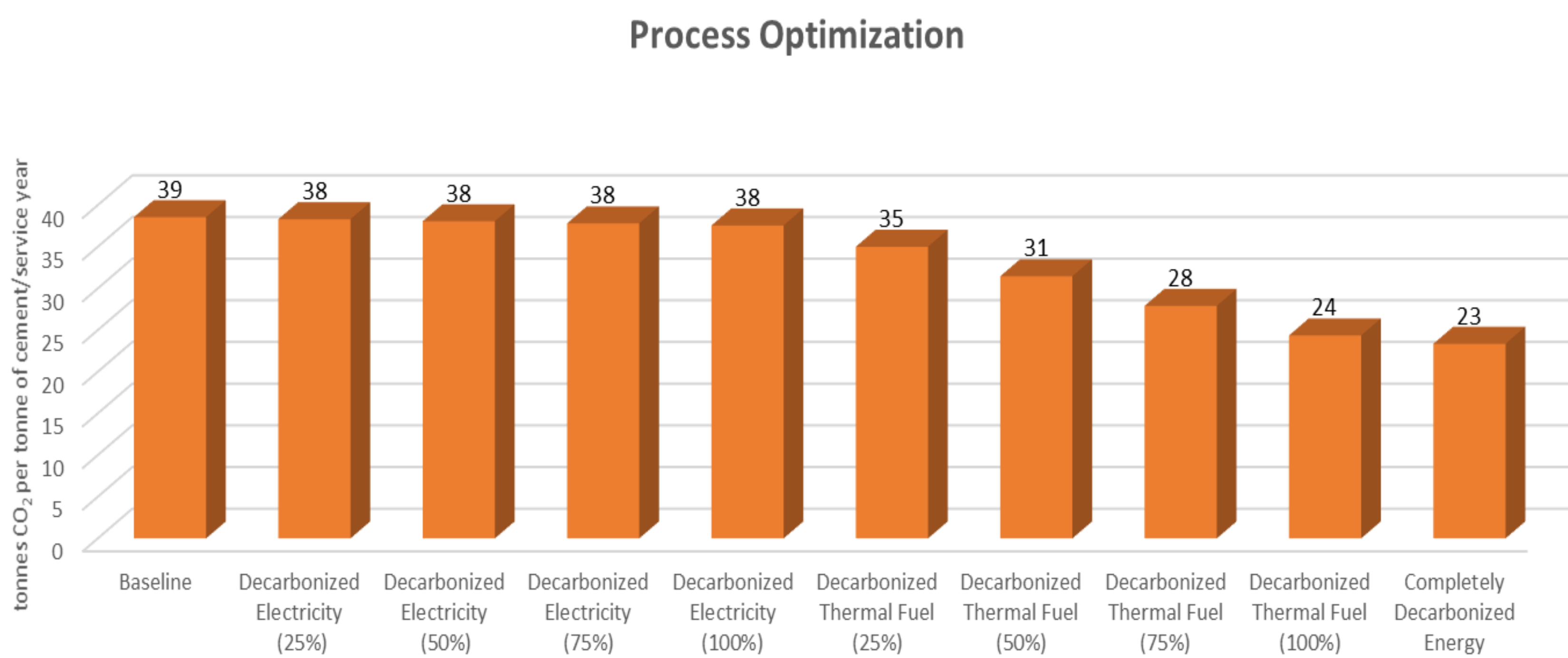


*Figure 6.3: Process Optimization (Energy Decarbonization) – 20 years*

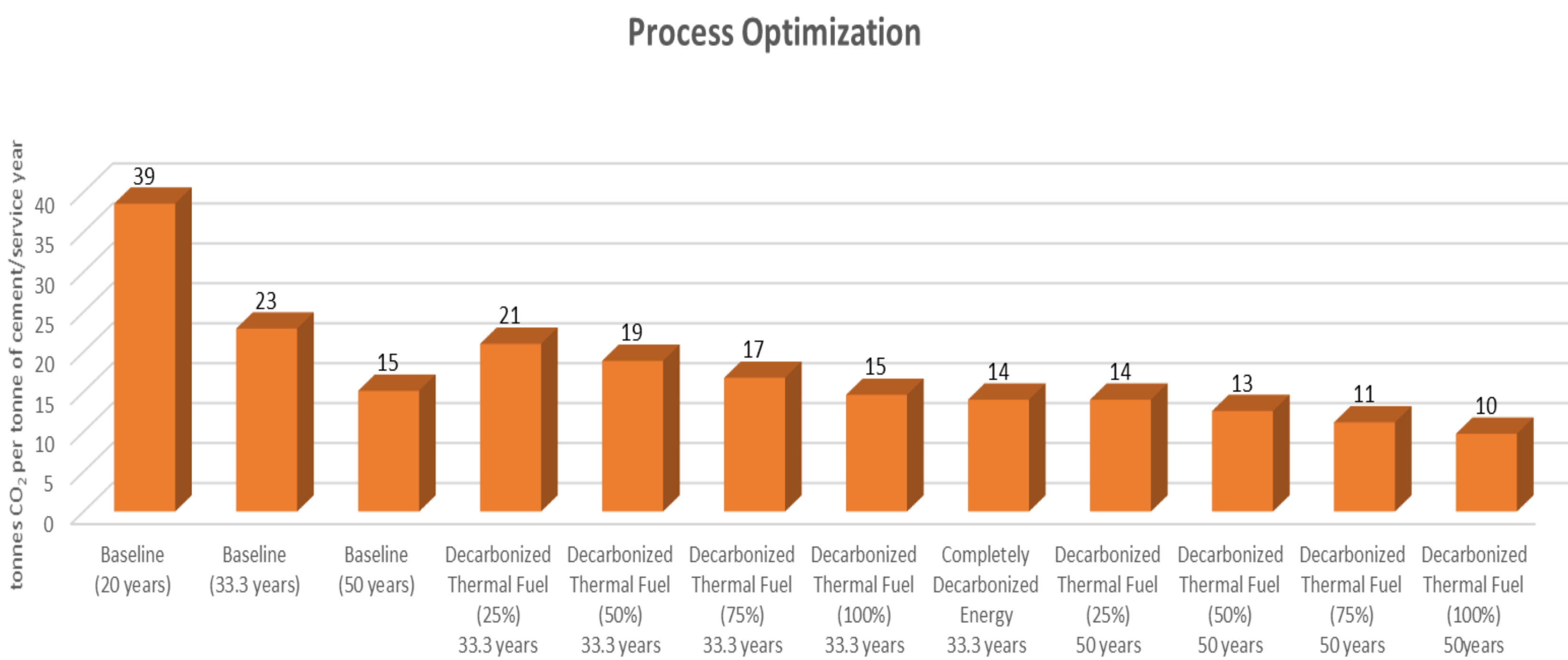


Figure 6.4: Process Optimization (Energy Decarbonization – 33.3 and 50-year service life)

Figure 6.4 compares the impact of decarbonization of thermal energy at 25, 50, 75, and 100% as well as a complete decarbonization of energy sources for a service life of 33.3 and 50 years. Figure 6.4 demonstrates that CIPS can be further reduced with the increase of service life in combination with process optimization/decarbonization. For completeness, the baseline values of a 33.3 and 50 years are included in Figure 6.4.

The addition of limestone to cement, offsetting a percentage of clinker and bypassing the carbon intensive clinker production process, is evaluated as a potential for process optimization. Limestone addition is captured in process optimization rather than industrial symbiosis as it can be classified as the decarbonization of raw material inputs with respect to cement manufacturing. This is logical as limestone is part of the same manufacturing process. Specifically, all the impact of limestone manufacturing including carbon emissions from extraction onwards are captured in the cement manufacturing process. This is fundamentally different from industrial symbiosis where the benefit of the material is assessed but the impacts are accounted for by a different industry or process.

Figure 6.5 shows the benefit associated with limestone addition of 5, 15, and 35 percent. These values are chosen as the current Canadian average is 4% with a 15% regulatory limit while the EU limit is 35% (Cement Association of Canada, 2020; WBCSD, 2015). As expected, the assessment at 5% limestone addition creates very little incremental benefit as this is only a 1% increase over the baseline. For addition of 15 and 35%, CIPS values range from 10 to 33 depending on the percentage of limestone addition and service life. It is clear that as an avoidance mechanism, limestone addition to cement can reach levels equivalent to complete decarbonization of energy.

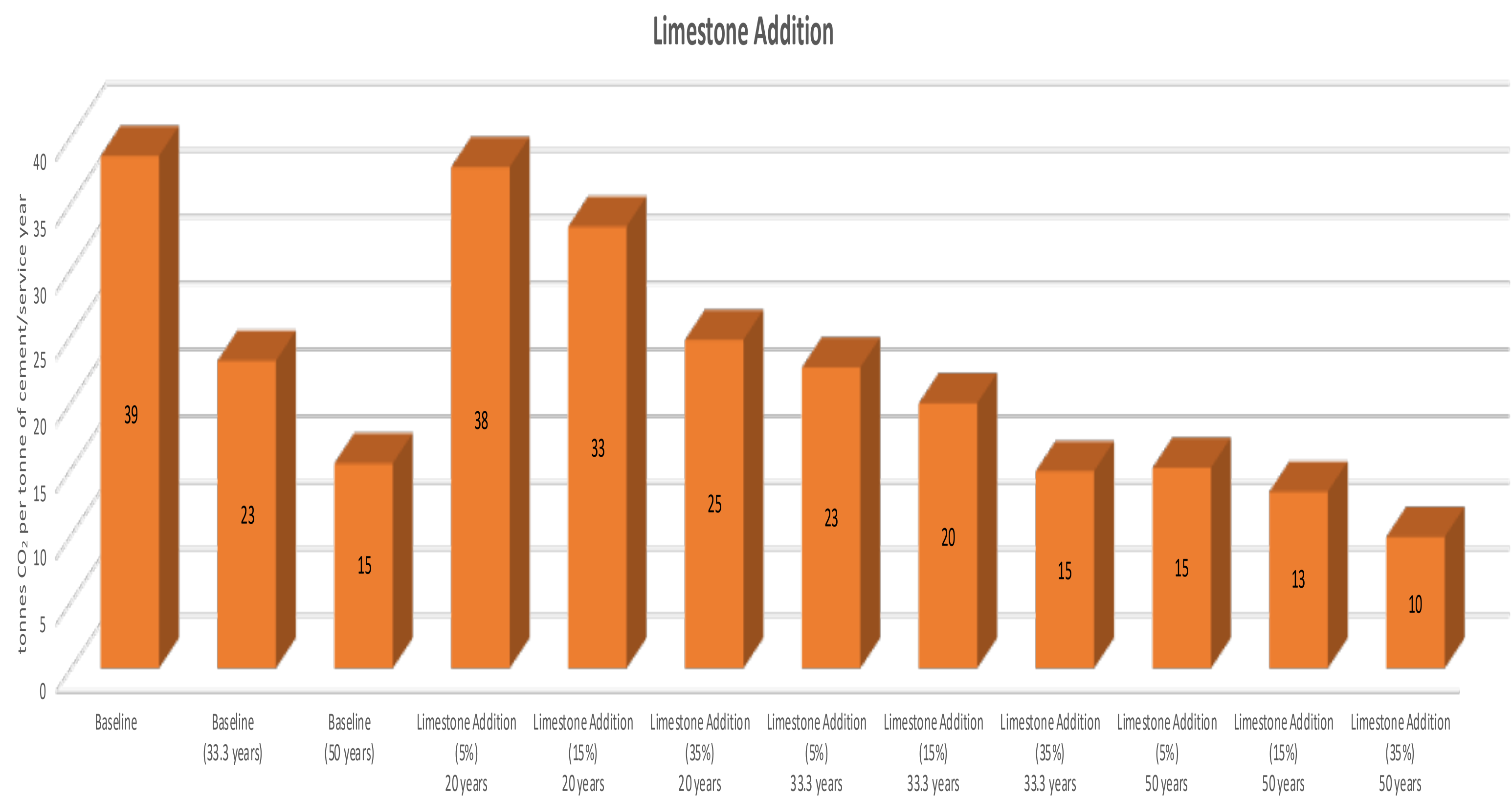


*Figure 6.5: Process Optimization (Limestone Addition @ 5, 15, and 35% – 20, 33.3 and 50-year service life)*

The conclusion from the information presented in this section is that numerous scenarios of service life extension and limestone addition will produce a lower CIPS value than process optimization until process optimization/decarbonization exceed 50% from existing levels. Further to this, as these actions are not mutually exclusive, the combination of extending service life and adding limestone to cement while decarbonizing energy inputs will surpass independent efforts.

### 6.4 Stretching

#### 6.4.1 Industrial Symbiosis

Industrial Symbiosis, the mutually beneficial exchange of materials between industries is evaluated as the primary opportunity that is already well documented in the cement industry (Ammenberg et al., 2015). Specifically, the use of blast furnace slag (BFS) – a by-product of the steelmaking industry – is used as a Mineral Component (MIC) to displace a certain portion of cement in concrete. According to the North American Slag Association (Slag Cement Association, 2013) the percentage of slag substitution can reach as high as 80%, leaving only 20% Ordinary Portland Cement (OPC) in the concrete mix.

Fly ash is also a common cement substitute that is a by-product of coal-fired power plants. As Canada has committed to shutting down all coal-fired power plants by 2030 along with 32 other national and 28 sub-national government (PPCA, 2020), it is expected that the availability of fly ash as a cement additive will not exist beyond the first production cycle in any of the scenarios analyzed. Specifically, at 20-year service life for cement produced this year (2020) will result in the 2nd production cycle in 2040, beyond the coal power elimination commitment by the Government of Canada (Canada, 2019).

Figure 6 shows the CIPS values associated with the use of blast furnace slag up to 80% (Slag Cement Association, 2013). It is clearly demonstrated that mineral components can create a significant reduction of carbon dioxide emissions as this is direct displacement of clinker that is responsible for the vast majority of carbon dioxide emissions in cement manufacturing.

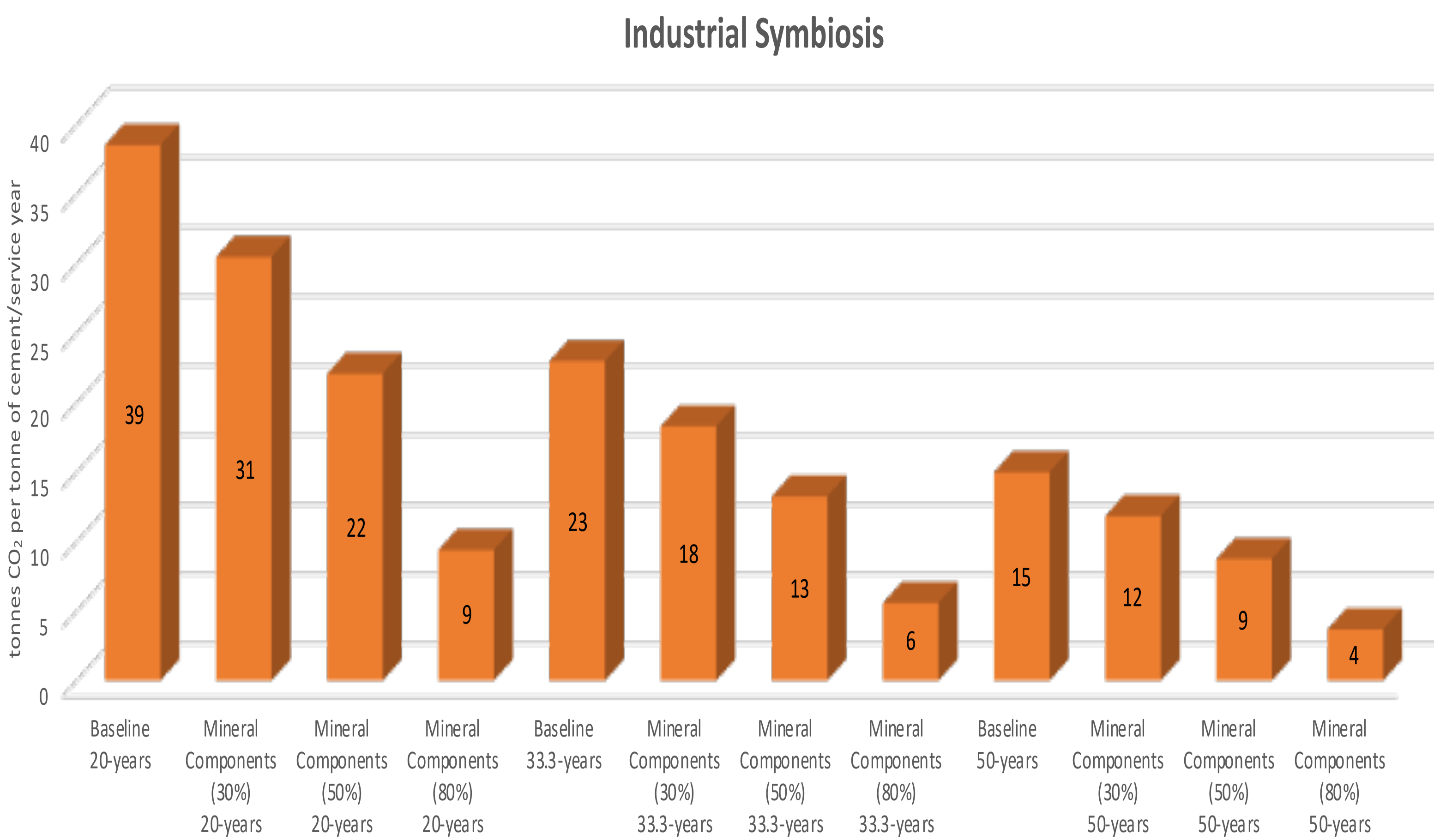


*Figure 6.6: Industrial Symbiosis (MIC @ 30, 50, 80%; 20, 33.3 and 50-years)*

Mineral components, primarily blast furnace slag, are being stretched in the cement manufacturing process. This is critically important in the carbon hierarchy as the carbon dioxide emissions that are avoided in cement manufacturing are a result of emissions from the steel industry to produce the slag. As such, the initial release of carbon dioxide emissions is being extended with the secondary use of blast furnace slag rather than the release of additional carbon dioxide emissions to manufacturer cement.

Carbon stretching, through industrial symbiosis, allows the cement industry to reduce carbon dioxide emissions by displacing clinker with an (essentially) carbon neutral cementitious material. This material in the model is captured as a carbon neutral additive that can displace clinker or, more accurately in Canada, displace OPC. While this is an acceptable approach to capture the CIPS value, there are several important qualitative considerations that are required to accurately capture the impact.

Firstly, the CaO in slag cannot be considered for potential uptake in the model unless the associated $CO_2$ emissions from producing slag are also included. This way, the potential benefits of slag are not double counted – i.e. captured but not emitted. This is especially important if the steel industry uses the same carbon hierarchy approach to capture its additive $CO_2$ impact and included sequestration value from slag as a lever.

Secondly, since BFS is a cement substitute rather than an interground material – the reduction requirement of the cement industry (total additive impact) must consider the quantity of BFS as a cement product in the market. This notion is the same for all cement substitutes in the concrete mix. What this means is that the calculation of the impact of the cement facility must include the total sales of cementitious material including materials such as BFS and fly ash. In this scenario, the value of industrial symbiosis is captured but does not miss the requirement of the cement industry to achieve carbon neutrality within its process when calculating absolute emissions.

The beneficial use of BFS as a cementitious material supports not only the provision of a beneficial material to displace clinker but also respects conservation of natural resources since the production of cement (without BFS) would result in higher extraction of raw materials to meet market demand.

It is important to note that with the inclusion of BFS, the CIPS changes units to tonnes $CO_2$ per tonne of cementitious material/service life. When calculating the potential reduction required for the cement plant to achieve carbon neutrality, the total amount of cementitious material must be used to calculate the overall additive impact. To simplify, if BFS is used in the denominator to calculate a specific per tonne emission then the quantity of BFS must also be included when calculating the absolute value of $CO_2$ emissions.

From a carbon hierarchy standpoint, this explains why industrial symbiosis should be below Avoidance but above Sequestration with respect to the decision-making process for carbon reductions in cement manufacturing.

### 6.4.2 Material Circularity

Material circularity is the evaluation of end-of-life (EOL) concrete use as raw material and clinker substitution as described in the model structure of Chapters 4. Material circularity, like industrial symbiosis, respects conservation of materials but unlike industrial symbiosis all the carbon emissions associated with production are included in the calculation. Considering all carbon output is captured in the evaluation of material circularity, carbon uptake that is specific to cement manufacturing should be included in the calculations.

The data presented consider the same continuous application of the cement in concrete products. If the original cement used for concrete that was Exposed with a strength of 15-20 MPa then the cement produced from the EOL concrete will again be used in a Exposed application at 15-20 MPa. This assumption does not have a significant impact on the model assessment but should be optimized by adjusting uses and strengths as well as representing jurisdiction specific uses (as is done in chapter 7).

The material circulariy assessment includes:
A) Baseline Scenario
B) Raw Material Substitution Scenario
C) Clinker Substitution Scenario

The production of cement in Canada for the 20, 33.3, and 50 year concrete service life are shown in Figure 6.7 for raw material and clinker substitution from EOL concrete. The data represents the results associates with median carbon dioxide uptake (specifically 2.5 mm $\sqrt{year}$). Figure 6.8, 6.9, and 6.10 along with Table 6.3 show the calculation for each application and strength for 20, 33.3, and 50 year, respectively.

The radar graphs in Figure 6.8, 6.9, and 6.10 show that, depending on the concrete mix, either substitution scenarios could be beneficial ranging in CIPS values from 26 to 38 in the 20-year service life scenarios, 14 to 23 in the 33.3-year service life scenarios, and 8 to 15 in the 50-year service life scenarios. The radar graphs reaffirm the finding from Chapter 5 that raw material substitution results in lower additive $CO_2$ emissions than clinker substitution regardless of the application shown as the CIPS value on each spoke (the spokes represent the application of concrete). The variability with each application (spoke) is the result of $CO_2$ uptake and available CaO that is dependent on application (*k value* for $CO_2$ penetration from Chapters 4 and 5).

| Service Life | 20 years | | 33.3 years | | 50 years | |
|---|---|---|---|---|---|---|
| Strength and Applicaton | Raw Material Substitution | Clinker Substitution | Raw Material Substitution | Clinker Substitution | Raw Material Substitution | Clinker Substitution |
| Wet <15 MPa | 34 | 37 | 21 | 22 | 14 | 14 |
| Wet 15-20 MPa | 35 | 38 | 21 | 22 | 14 | 15 |
| Wet 25-30 MPa | 35 | 38 | 21 | 23 | 14 | 15 |
| Wet > 35 MPa | 35 | 38 | 21 | 23 | 14 | 15 |
| Buried <15 MPa | 34 | 36 | 20 | 21 | 13 | 14 |
| Buried 15-20 MPa | 35 | 37 | 21 | 22 | 14 | 15 |
| Buried 25-30 MPa | 35 | 38 | 21 | 22 | 14 | 15 |
| Buried > 35 MPa | 35 | 38 | 21 | 23 | 14 | 15 |
| Exposed <15 MPa | 32 | 35 | 19 | 20 | 12 | 13 |
| Exposed 15-20 MPa | 34 | 37 | 20 | 22 | 14 | 14 |
| Exposed 25-30 MPa | 35 | 37 | 21 | 22 | 14 | 15 |
| Exposed > 35 MPa | 35 | 38 | 21 | 22 | 14 | 15 |
| Sheltered <15 MPa | 29 | 31 | 16 | 17 | 10 | 11 |
| Sheltered 15-20 MPa | 32 | 34 | 19 | 20 | 12 | 13 |
| Sheltered 25-30 MPa | 33 | 35 | 20 | 21 | 13 | 13 |
| Sheltered > 35 MPa | 34 | 37 | 20 | 22 | 14 | 14 |
| Indoor <15 MPa | 26 | 27 | 14 | 14 | 8 | 8 |
| Indoor 15-20 MPa | 30 | 32 | 17 | 18 | 11 | 11 |
| Indoor 25-30 MPa | 32 | 34 | 19 | 20 | 12 | 13 |
| Indoor > 35 MPa | 33 | 36 | 20 | 21 | 13 | 14 |

*Table 6.3: Material Circularity – Raw Material and Clinker Substitution (20, 33.3, and 50-years)*

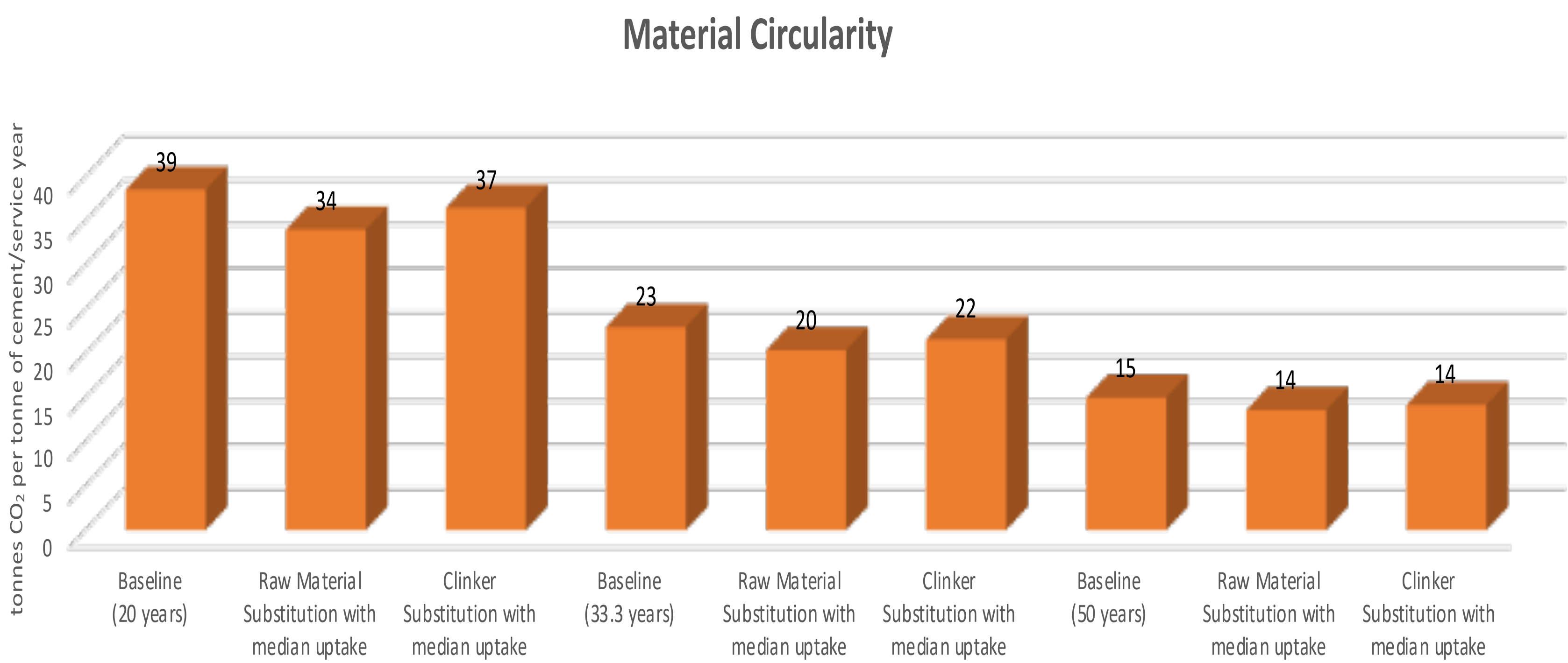


*Figure 6.7: Material Circularity – Raw Material and Clinker Substitution (Median) 20, 33.3, and 50-year*

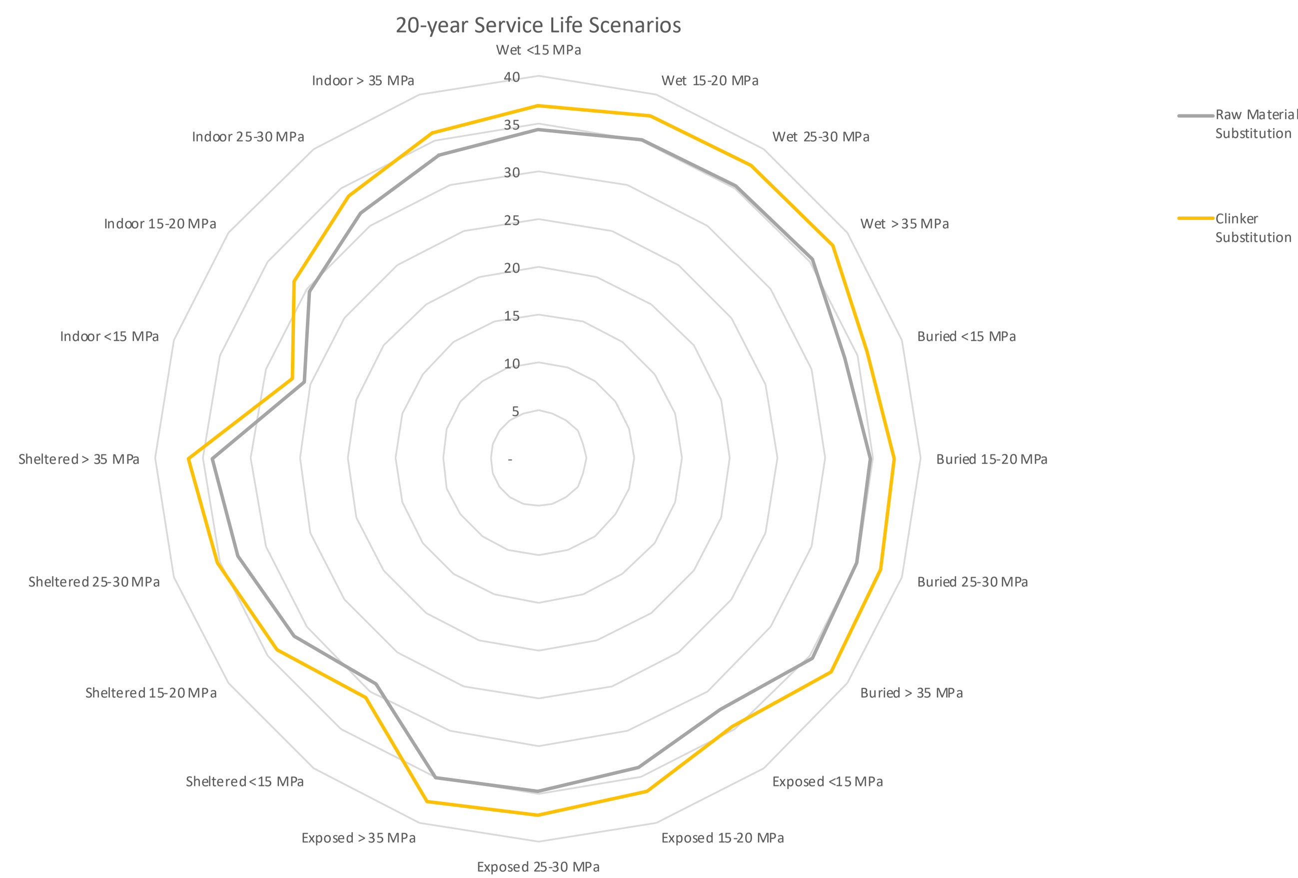


*Figure 6.8: Material Circularity – Raw Material and Clinker Substitution (20-years)*

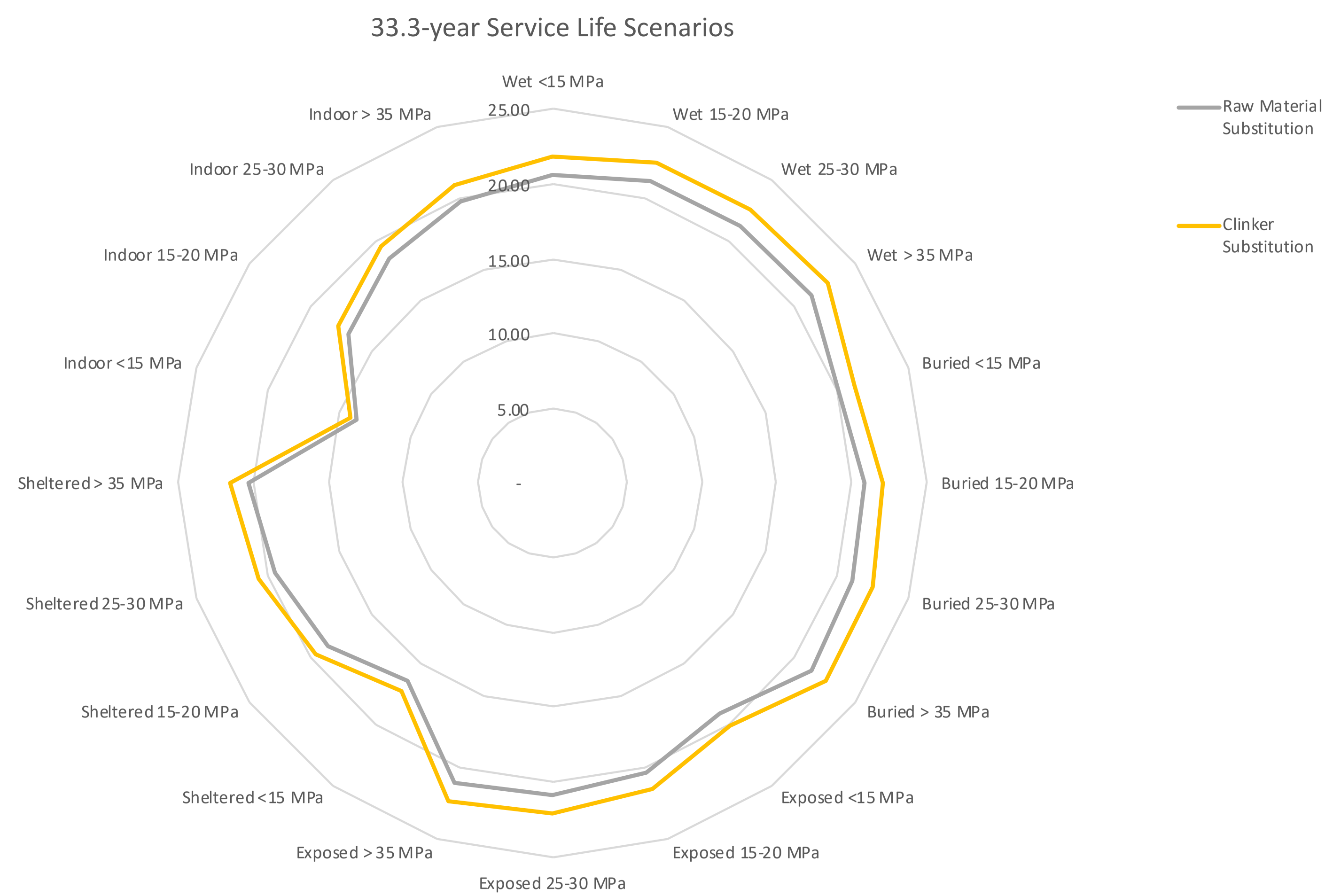


*Figure 6.9: Material Circularity – Raw Material and Clinker Substitution (33.3-years)*

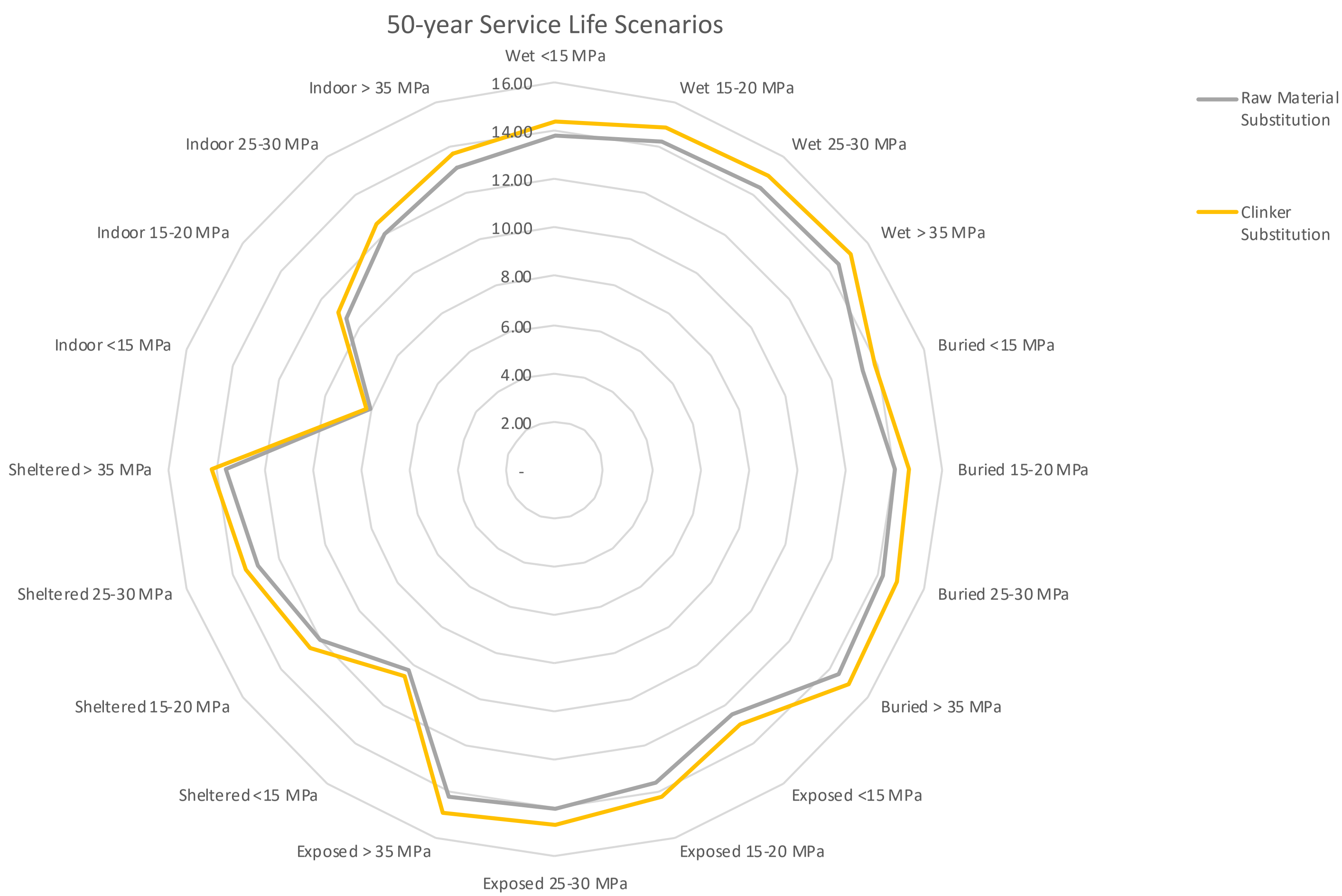


*Figure 6.10: Material Circularity – Raw Material and Clinker Substitution (50-years)*

Based on this empirical evidence, it is clear that Material Circularity has a role to play in the reduction of carbon dioxide emissions associated with the cement industry. Material circularity does not avoid emissions in the manufacturing process to the extent service life extension or process optimization does. However, the reintroduction of EOL concrete into the manufacturing process does reduce the carbon dioxide emissions while respecting the conservation of natural raw materials by reusing the same materials rather than extracting virgin materials.

The reductions evaluated are not mutually exclusive until material circularity is reached. Material circularity, specifically the choice between the use of EOL concrete for raw material or clinker substitution, is the first decision juncture in the carbon hierarchy. With the information presented in this section, the best choice with respect to total additive carbon emissions is raw material substitution. However, in many scenarios the results for raw material and clinker substitution are quite close so depending on the other carbon dioxide reduction measures implemented in Avoidance, the choice for EOL concrete use may change.

## 6.5 Sequestration

Sequestration, the final level in the carbon hierarchy, can generally be achieved in two fundamental ways, either through carbon capture and utilization (CCU) or carbon capture and storage (CCS). Carbon capture and storage is considered the final option in the Carbon Hierarchy as it simply prevents the carbon from being released to the natural environment. Carbon capture and utilization, on the other hand, captures the carbon dioxide in a material that provide a further use. With respect to the Carbon Hierarchy for cement, CCU can achieve carbon dioxide uptake in aggregate for further use in construction applications.

Aggregate is explicitly considered carbon capture and utilization as the material is not returned through material circularity. Although aggregates continue to asborb carbon dioxide, the unreacted cement material that could be stretched for additional use is simply used as a carbon sink. The same would be true is BFS would be used for aggregate rather than as a cement substitute, even if the additive carbon dioxide emissions are the same or lower than the value of the material is as a carbon sink.

The production of cement in Canada for the 20, 33.3, and 50 year concrete service life are shown in Figure 6.11 with aggregate production/utilization from EOL concrete. The data represents the results associated with median carbon dioxide uptake (specifically 2.5 mm $\sqrt{year}$). Figure 6.12, 6.13, and 6.14 with Table 6.4 show the calculations for each application and strength for 20, 33.3, and 50 year, respectively. As expected, the smaller aggregate size (22.4 mm) results in a lower CIPS value due to a higher surface area for carbon dioxide uptake. The larger size (250 mm) is used for comparison as it represents limited processing since the initial concrete thickness is 250 mm. Aggregate sizes represent the maximum size of Recycled Concrete Aggregate (RCA) of 22.4 mm and approximate size of larger size erosion control/rip rap material of 250 mm (Dufferin Aggregates, 2019).

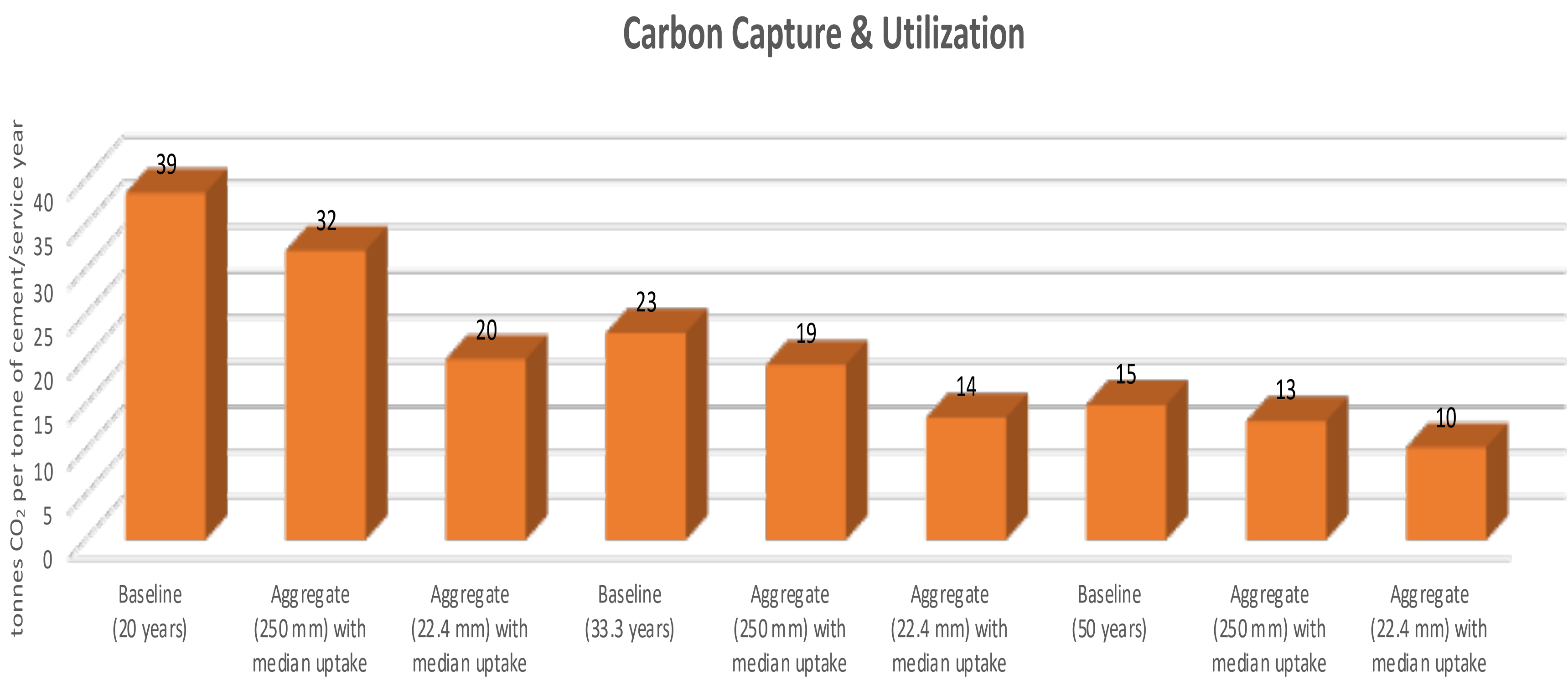


*Figure 6.11: Carbon Capture and Utilization – Aggregate 250 mm and 22.4 mm (Median) 20, 33.3, and 50-years*

The radar graphs in Figure 6.12, 6.13, and 6.14 include scenarios for raw material substitution, clinker substitution, and aggregate utilization (22.4 mm nomimal size). These figures show that, depending on the concrete mix, CIPS values range from 19 to 26 in the 20-year service life scenarios, 11 to 17 in the 33.3-year service life scenarios, and 7 to 11 in the 50-year service life scenarios.

Figure 6.12 – 6.14 also include value for 22.4 mm aggregate with error. These values are included since overlap error, as presented in Chapter 4, can have a significant impact as surface area increases. This error is apparent in applications where uptake is significant due to k-factor, specifically *Indoor* and *Sheltered* concrete with strength *<15 MPa*.

The radar graphs reaffirm the finding from Chapter 5 that Raw Material Substitution results in lower additive $CO_2$ emissions than Clinker Substitution regardless of the application (shown as the CIPS value on each spoke). These graphs also reaffirm that Aggregate utilization generates the most significant reduction in additive $CO_2$ emissions.

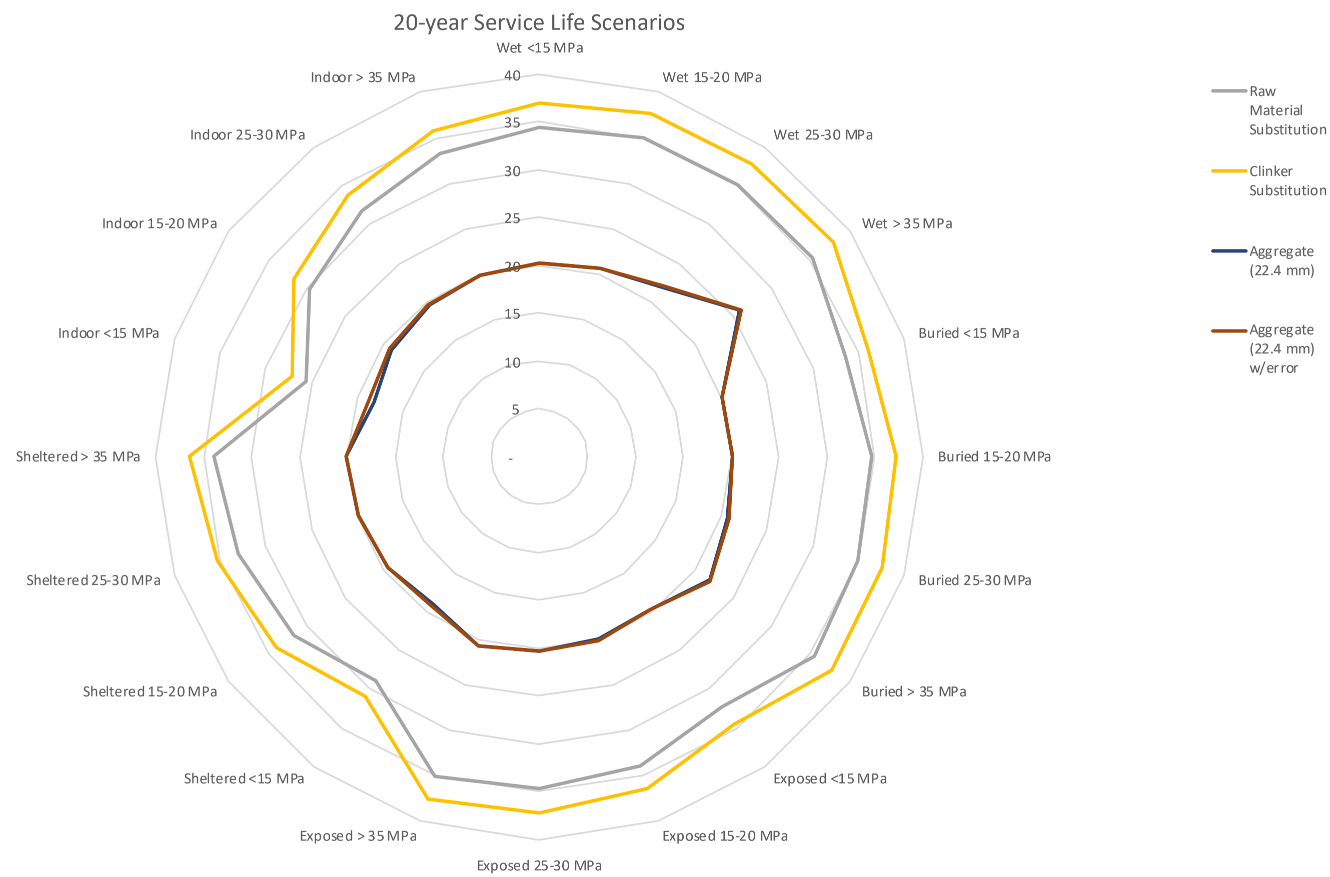


*Figure 6.12: Carbon Capture and Utilization – Raw Material/Clinker Substitution and Aggregate Use (20-years)*

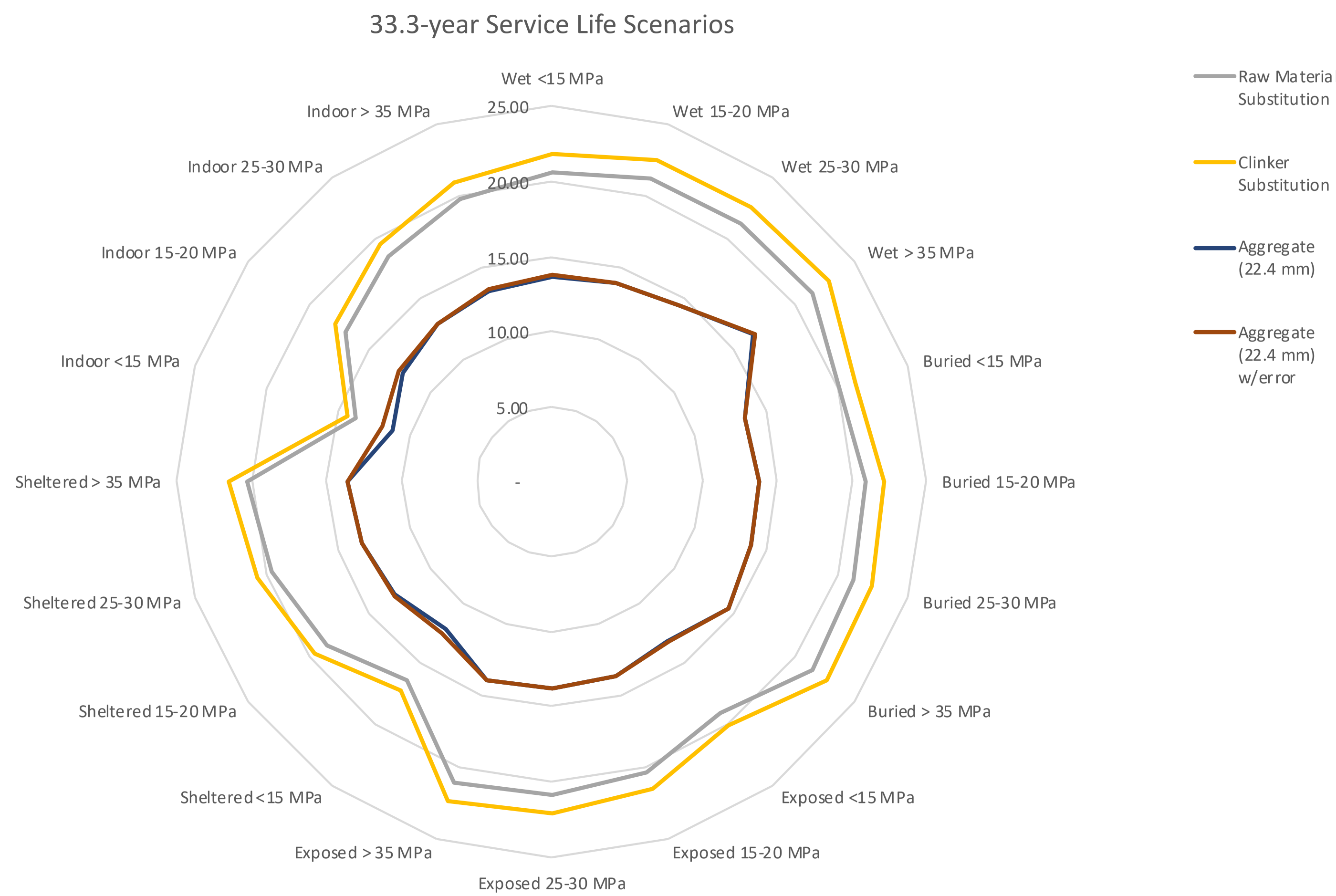


*Figure 6.13: Carbon Capture and Utilization – Raw Material/Clinker Substitution and Aggregate Use (33.3-years)*

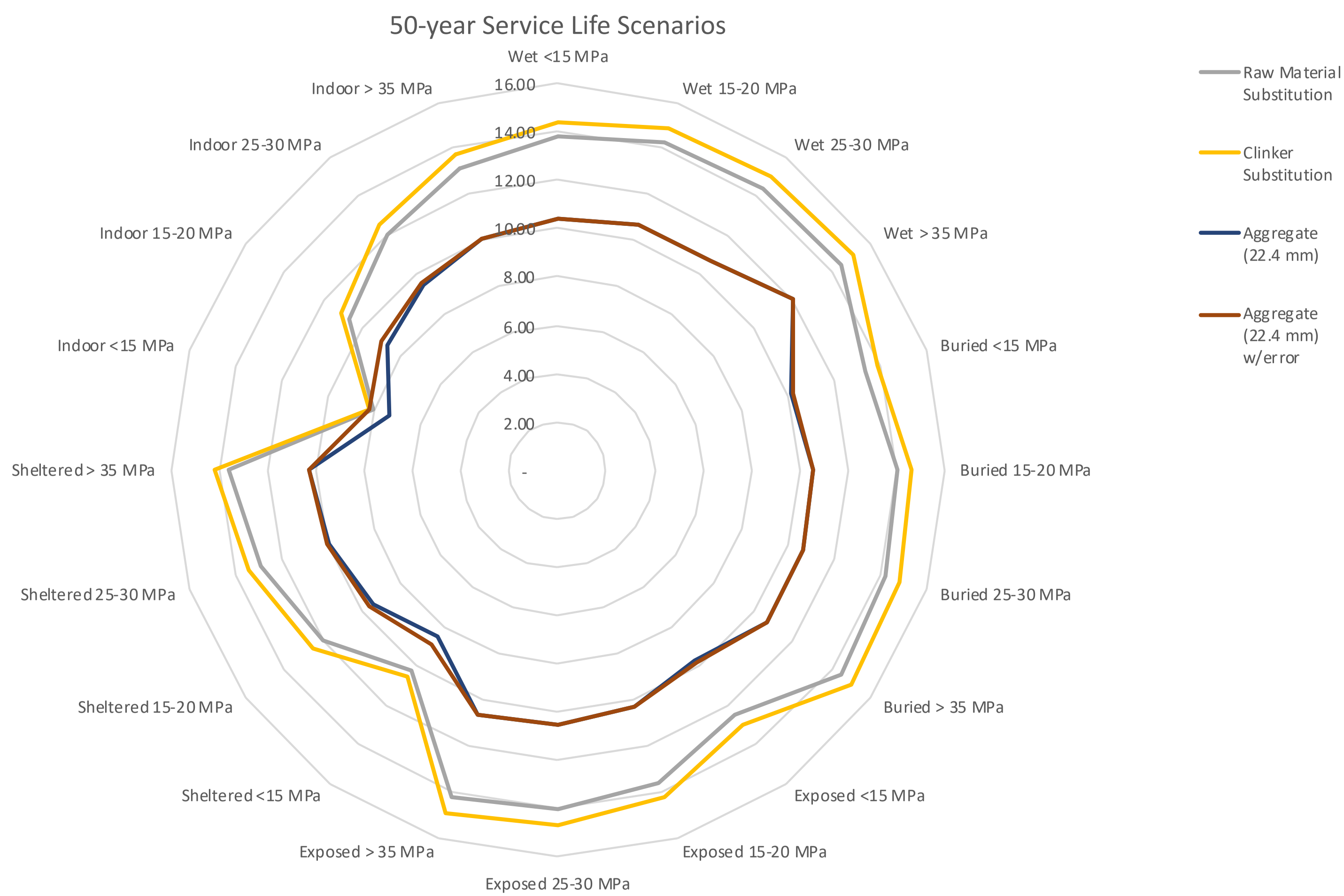


*Figure 6.14: Carbon Capture and Utilization – Raw Material/Clinker Substitution and Aggregate Use (50-years)*

| Service Life | 20 years | | | | 33.3 years | | | | 50 years | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Strength and Applicaton | Raw Material Substitution | Clinker Substitution | Aggregate (22.4 mm) | Aggregate (22.4 mm) w/error | Raw Material Substitution | Clinker Substitution | Aggregate (22.4 mm) | Aggregate (22.4 mm) w/error | Raw Material Substitution | Clinker Substitution | Aggregate (22.4 mm) | Aggregate (22.4 mm) w/error |
| Wet <15 MPa | 34 | 37 | 20 | 20 | 21 | 22 | 14 | 14 | 14 | 14 | 10 | 10 |
| Wet 15-20 MPa | 35 | 38 | 21 | 21 | 21 | 22 | 14 | 14 | 14 | 15 | 11 | 11 |
| Wet 25-30 MPa | 35 | 38 | 22 | 22 | 21 | 23 | 14 | 15 | 14 | 15 | 11 | 11 |
| Wet > 35 MPa | 35 | 38 | 26 | 26 | 21 | 23 | 17 | 17 | 14 | 15 | 12 | 12 |
| Buried <15 MPa | 34 | 36 | 20 | 20 | 20 | 21 | 13 | 14 | 13 | 14 | 10 | 10 |
| Buried 15-20 MPa | 35 | 37 | 20 | 20 | 21 | 22 | 14 | 14 | 14 | 15 | 11 | 11 |
| Buried 25-30 MPa | 35 | 38 | 21 | 21 | 21 | 22 | 14 | 14 | 14 | 15 | 11 | 11 |
| Buried > 35 MPa | 35 | 38 | 22 | 22 | 21 | 23 | 14 | 15 | 14 | 15 | 11 | 11 |
| Exposed <15 MPa | 32 | 35 | 20 | 20 | 19 | 20 | 13 | 13 | 12 | 13 | 10 | 10 |
| Exposed 15-20 MPa | 34 | 37 | 20 | 20 | 20 | 22 | 14 | 14 | 14 | 14 | 10 | 10 |
| Exposed 25-30 MPa | 35 | 37 | 20 | 20 | 21 | 22 | 14 | 14 | 14 | 15 | 11 | 11 |
| Exposed > 35 MPa | 35 | 38 | 21 | 21 | 21 | 22 | 14 | 14 | 14 | 15 | 11 | 11 |
| Sheltered <15 MPa | 29 | 31 | 19 | 19 | 16 | 17 | 12 | 12 | 10 | 11 | 8 | 9 |
| Sheltered 15-20 MPa | 32 | 34 | 20 | 20 | 19 | 20 | 13 | 13 | 12 | 13 | 9 | 10 |
| Sheltered 25-30 MPa | 33 | 35 | 20 | 20 | 20 | 21 | 13 | 13 | 13 | 13 | 10 | 10 |
| Sheltered > 35 MPa | 34 | 37 | 20 | 20 | 20 | 22 | 14 | 14 | 14 | 14 | 10 | 10 |
| Indoor <15 MPa | 26 | 27 | 18 | 19 | 14 | 14 | 11 | 12 | 8 | 8 | 7 | 8 |
| Indoor 15-20 MPa | 30 | 32 | 19 | 19 | 17 | 18 | 12 | 13 | 11 | 11 | 9 | 9 |
| Indoor 25-30 MPa | 32 | 34 | 20 | 20 | 19 | 20 | 13 | 13 | 12 | 13 | 9 | 10 |
| Indoor > 35 MPa | 33 | 36 | 20 | 20 | 20 | 21 | 13 | 13 | 13 | 14 | 10 | 10 |

*Table 6.4: Carbon Capture and Utilization – Raw Material/Clinker Substitution & Aggregate Use (20, 33.3, & 50-years)*

### 6.6 Conclusion

The quantitative evaluation of the cement industry in this chapter aimed to address the following hypothesis: *If a successive stage hierarchy for carbon mitigation and material circularity is created it would ensure rational carbon reduction and resource conservation decision-making in the cement industry.*

This hypothesis was tested with various scenarios of carbon dioxide emission reductions showing that ***the Carbon Hierarchy is a successive stage hierarchy for carbon mitigation and circularity ensuring rational carbon reduction and resource conservation decision-making in the cement industry.***

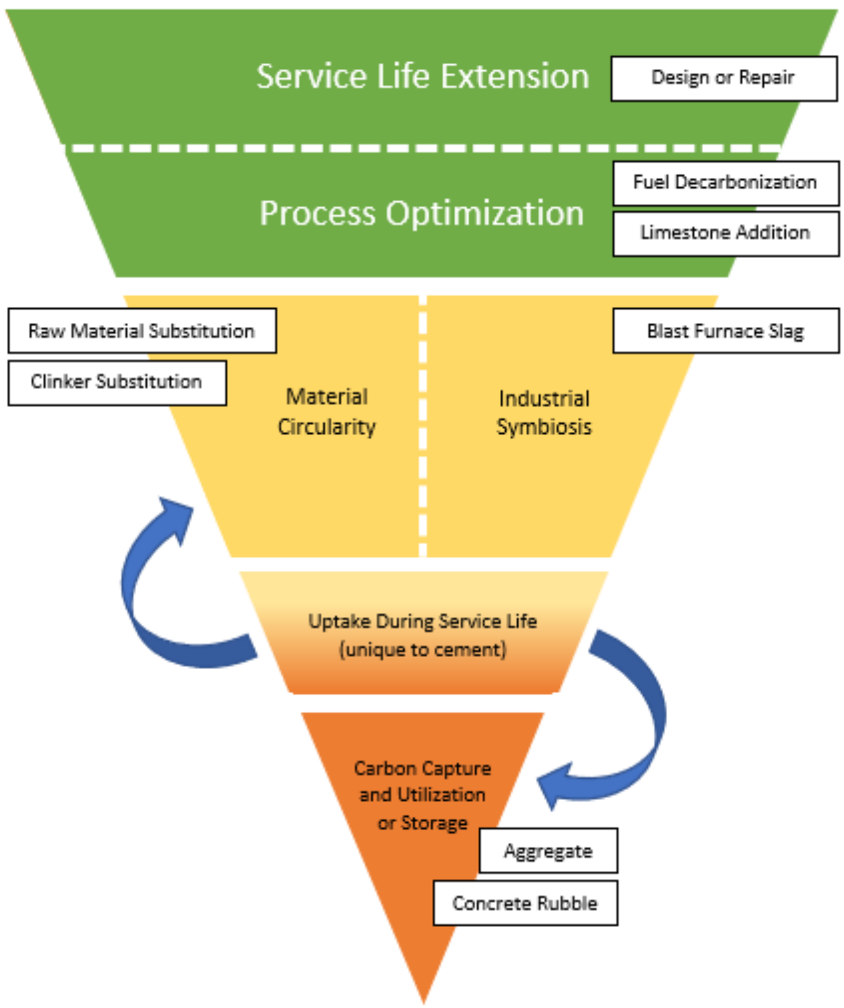


*Figure 6.15: Carbon Hierarchy for Cement Manufacturing*

The hypothesis is verified by showing that each stage of the Carbon Hierarchy reduces the additive carbon emission and at the juncture points of carbon reduction and resource conservation, the user has the ability to validate decisions based on the structure of the Carbon Hierarchy. These juncture points, specific to cement, are the use of end-of-life concrete either for raw material substitution, clinker substitution or for aggregate, as shown with the arrows in Figure 6.15. The Carbon Hierarchy clearly identifies that the first two options allow for resource conservation while the last option does not. It is clear that reduction potential exists at each level of the hierarchy and the specific quantity at each level is not as critical as the sequence that ensured that higher level actions do not prevent lower level actions.

It is critically important that the Carbon Hierarchy is intended to enable carbon and resource positive decision making rather than restricting it. This intention drives the requirement for flexible and robust system that is not too rigid that innovative solutions would require a restructuring of the hierarchy.

The data presented in this chapter do not explicitly derive a value as each level is independently evaluated. The following chapter shows the application of the actions within this successive stage hierarchy in a Canadian context of cement manufacturing and quantifies the gap to carbon neutrality.

# Chapter 7
# Application of the Carbon Hierarchy
# Canadian Jurisdiction

The following chapter presents a detailed assessment of the Carbon Hierarchy in a Canadian context. The generalized assessment of the Carbon Hierarchy in chapter 6 highlights the potential reductions that can be achieved in the Canadian cement industry, in general. However, the generalized assessment does not consider the specific application of end-of-life (EOL) concrete use. Within this chapter, the Canadian cement perspective is assessed to determine the amount of additive carbon dioxide emissions associated with cement manufacturing and addresses the second hypothesis presented in Chapter 3, namely: "*If such a system can be used to quantify the gap to reach carbon neutrality.*"

## 7.1 Overview

The assessment of the Carbon Hierarchy from a Canadian perspective in Chapter 6 highlights the potential reductions of carbon dioxide emissions that can be achieved in the Canadian cement industry, in general. However, the generalized assessment does not consider the specific application of end-of-life (EOL) concrete use. In this chapter, the Canadian cement perspective is assessed using the successive stage hierarchy and associated model to determine the amount of additive carbon dioxide emissions associated with cement manufacturing and the gap that each level of the hierarchy can address. The Canadian assessment also provides a stepwise approach of how the Carbon Hierarchy and the associated model can be applied to jurisdictional policymaking decisions or by individual cement operators to reach carbon neutrality.

## 7.2 Scope of the Canadian Assessment

The scope of the Canadian assessment considers the potential application of end-of-life concrete, the service life, and uptake error as presented in Chapter 4. The assessment considers both primary and secondary use with various applications of concrete. The primary applications of 'wet' or 'buried' concrete environments are excluded with the understanding that concrete applications in environments that are either submerged in water or buried underground will have specific design criteria with respect to strength and service life that may not warrant removal and reprocessing. Additionally, the extraction of submerged or buried material is less likely for reuse.

Secondary use of EOL concrete is also restricted to only exposed or buried application – specifically, above ground where gravel or crushed stone would otherwise be used or subgrade applications such as road base. It is not expected that the EOL concrete will be used for indoor or sheltered applications (in homes or building) or wet conditions where water quality aspects may dictate aggregate specifications.

As such, the primary uses are: 1) Exposed; 2) Sheltered; or 3) Indoor;

with the secondary uses being: 1) Exposed or 2) Buried.

The assessment considers the following scenarios in the order that these would be applied in the Carbon Hierarchy as highlighted in Chapter 6:

1) Life extension
2) Thermal Energy Decarbonization
3) Limestone Addition
4) Limestone Addition & Thermal Energy Decarbonization
5) EU Limestone Addition & Complete Energy Decarbonization

Each of the five scenarios evaluate the additive carbon emissions per tonne of cement produced with consideration for circulating the end-of-life concrete as raw material or clinker substitution as well as the carbon capture and utilization in 22.4 mm aggregate. As stated in Chapter 6, 22.4

mm aggregate is used as the largest diameter of crushed concrete (Dufferin Aggregates, 2019) resulting in a representation of market place material but the top end of sizing resulting in a more conservative assessment since uptake is a function of available surface area.

It should be noted that unlike Chapter 6 that compares values based on CIPS – all values in this chapter are assessed independently of one another across time periods. The values are presented as kilograms of additive carbon dioxide emissions per tonne of cement over a 100-year basis. The intention for this approach is that the additive carbon dioxide emissions values represent the gap between potential emissions levels and carbon neutrality. CIPS values provide an excellent comparison relative to the additive impact per unit of material but the assumption is that a facility producing cement for a 50-year service life concrete will continue to manufacture cement continuously rather than stop for the 50-years between the initial batch and the replacement batch 50-years later. It is due to this continuity of production that full values, adjusted for service life, in kilogram of carbon dioxide per kilogram of cement are presented in this chapter.

### 7.3 Methodology & Results

The results of the various scenarios are presented in Table 7.1. The output shows the kilograms of additive carbon dioxide emissions per tonne of cement for raw material substitution, clinker substitution, and aggregate use (22.4 mm nominal size).

Values for thermal substitution of 18% are obtained from the Germany average (WBCSD, 2015). The rationale for using these values is that Germany's MJ/t of cement is within 0.5% of Canada including material drying while the kg $CO_2$/MJ are 18% less. This suggests an improvement in carbon intensity of the entire thermal system rather than a different physical plant configuration or material chemistry that would result in lower thermal needs. Although these solutions are valid (especially change in physical configuration), the goal is to assess the potential decarbonization that is relatively easy to obtain (or mimic) rather than the complete decarbonatization goal that is presented as a different scenario.

The limestone addition values used are based on maximum allowable concentrations in Canada and the EU of 15% and 35%, respectively (Cement Association of Canada, 2020).

Finally, an assessment of complete decarbonization of energy systems including electrical systems is considered. This is the only scenario where limestone addition of 35% is used. This scenario is considered to be the best possible future state of the cement industry as it currently exists (ie. without a major transformation in how cement is manufactured). This also represents the maximum foreseeable avoidance of $CO_2$ emissions from the manufacturing process which, in combination with material circularity and carbon capture and utilization (CCU), would leave a remaining portion of $CO_2$ emissions that require management.

Industrial symbiosis, specifically the use of blast furnace slag, is not included in this assessment based on the rationale provided in Chapter 6. Table 7.1 shows each scenario that was tested based on the variables of service life, thermal energy decarbonization, limestone addition and three potential end-of-life options: raw material substitution; clinker substitution; or aggregate use.

Additional cement content is included in the assessment to capture a full range for the potential gap to carbon neutrality including partial repair or replacement.

| Scenario | Service Life | Process Optimization/ Decarbonization | Limestone Addition | Cement Content |
|---|---|---|---|---|
| Life Extension | 20-years | None | 4% | 11.0% |
| | 33.3-year, +10% cement | None | 4% | 12.1% |
| | 33.3-year, +20% cement | None | 4% | 13.2% |
| | 33.3-year, +30% cement | None | 4% | 14.3% |
| | 33.3-year, +40% cement | None | 4% | 15.4% |
| | 33.3-year, +50% cement | None | 4% | 16.5% |
| | 50-year, +10% cement | None | 4% | 12.1% |
| | 50-year, +20% cement | None | 4% | 13.2% |
| | 50-year, +30% cement | None | 4% | 14.3% |
| | 50-year, +40% cement | None | 4% | 15.4% |
| | 50-year, +50% cement | None | 4% | 16.5% |
| | 25% repair every 20-years | None | 4% | 11% |
| | 50% repair evey 20-years | None | 4% | 11% |
| Thermal Energy Decarbonization | 33.3-year, +10% cement | 18% Thermal Reduction | 4% | 12.1% |
| | 33.3-year, +20% cement | 18% Thermal Reduction | 4% | 13.2% |
| | 33.3-year, +30% cement | 18% Thermal Reduction | 4% | 14.3% |
| | 33.3-year, +40% cement | 18% Thermal Reduction | 4% | 15.4% |
| | 33.3-year, +50% cement | 18% Thermal Reduction | 4% | 16.5% |
| | 50-year, +10% cement | 18% Thermal Reduction | 4% | 12.1% |
| | 50-year, +20% cement | 18% Thermal Reduction | 4% | 13.2% |
| | 50-year, +30% cement | 18% Thermal Reduction | 4% | 14.3% |
| | 50-year, +40% cement | 18% Thermal Reduction | 4% | 15.4% |
| | 50-year, +50% cement | 18% Thermal Reduction | 4% | 16.5% |
| | 25% repair every 20-years | 18% Thermal Reduction | 4% | 11% |
| | 50% repair evey 20-years | 18% Thermal Reduction | 4% | 11% |
| Limestone Addition | 33.3-year, +10% cement | None | 15% | 12.1% |
| | 33.3-year, +20% cement | None | 15% | 13.2% |
| | 33.3-year, +30% cement | None | 15% | 14.3% |
| | 33.3-year, +40% cement | None | 15% | 15.4% |
| | 33.3-year, +50% cement | None | 15% | 16.5% |
| | 50-year, +10% cement | None | 15% | 12.1% |
| | 50-year, +20% cement | None | 15% | 13.2% |
| | 50-year, +30% cement | None | 15% | 14.3% |
| | 50-year, +40% cement | None | 15% | 15.4% |
| | 50-year, +50% cement | None | 15% | 16.5% |
| | 25% repair every 20-years | None | 15% | 11% |
| | 50% repair evey 20-years | None | 15% | 11% |
| Limestone Addition + Thermal Energy Decarbonization | 33.3-year, +10% cement | 18% Thermal Reduction | 15% | 12.1% |
| | 33.3-year, +20% cement | 18% Thermal Reduction | 15% | 13.2% |
| | 33.3-year, +30% cement | 18% Thermal Reduction | 15% | 14.3% |
| | 33.3-year, +40% cement | 18% Thermal Reduction | 15% | 15.4% |
| | 33.3-year, +50% cement | 18% Thermal Reduction | 15% | 16.5% |
| | 50-year, +10% cement | 18% Thermal Reduction | 15% | 12.1% |
| | 50-year, +20% cement | 18% Thermal Reduction | 15% | 13.2% |
| | 50-year, +30% cement | 18% Thermal Reduction | 15% | 14.3% |
| | 50-year, +40% cement | 18% Thermal Reduction | 15% | 15.4% |
| | 50-year, +50% cement | 18% Thermal Reduction | 15% | 16.5% |
| | 25% repair every 20-years | 18% Thermal Reduction | 15% | 11% |
| | 50% repair evey 20-years | 18% Thermal Reduction | 15% | 11% |
| EU Limestone Addition + Complete Energy Decarbonization | 50-year, +10% cement | 100% Decarbonation | 35% | 12.1% |
| | 50-year, +20% cement | 100% Decarbonation | 35% | 13.2% |
| | 50-year, +30% cement | 100% Decarbonation | 35% | 14.3% |
| | 50-year, +40% cement | 100% Decarbonation | 35% | 15.4% |
| | 50-year, +50% cement | 100% Decarbonation | 35% | 16.5% |
| | 25% repair every 20-years | 100% Decarbonation | 35% | 11% |

*Table 7.1: Canadian Scenario Inputs*

As presented in Chapter 4, a potential error exists with overlapping calculations of carbon dioxide uptake. Table 7.2 presents the error associated with the potential reduction of overall uptake to 75% of full recarbonation (T. Carb = 0.75 as discussed in Chapter 4). The error values are included in the output results presented in Figures 7.1, 7.2, 7.15, 7.22, 7.29, 7.36, 7.43, 7.50, and 7.57.

| | | | | | Raw Material Substitution | | | Clinker Substitution | | | Aggregate (22.4 mm) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Scenario | Service Life | Process Optimization/ Decarbonization | Limestone Addition | Cement Content | RM Max | RM Min | RM Median | Clinker Max | Clinker Min | Clinker Median | Agg Max | Agg Min | Agg Median |
| Life Extension | 20-years | None | 4% | 11.0% | 0% | 4% | 0% | 0% | 0% | 0% | 13% | 22% | 19% |
| | 33.3-year, +10% cement | None | 4% | 12.1% | 0% | 4% | 1% | 0% | 0% | 0% | 11% | 22% | 15% |
| | 33.3-year, +20% cement | None | 4% | 13.2% | 0% | 5% | 1% | 0% | 0% | 0% | 11% | 22% | 15% |
| | 33.3-year, +30% cement | None | 4% | 14.3% | 0% | 5% | 1% | 0% | 0% | 0% | 11% | 22% | 15% |
| | 33.3-year, +40% cement | None | 4% | 15.4% | 0% | 5% | 1% | 0% | 0% | 0% | 11% | 22% | 15% |
| | 33.3-year, +50% cement | None | 4% | 16.5% | 0% | 5% | 1% | 0% | 0% | 0% | 11% | 22% | 15% |
| | 50-year, +10% cement | None | 4% | 12.1% | 0% | 9% | 0% | 0% | 5% | 0% | 10% | 25% | 10% |
| | 50-year, +20% cement | None | 4% | 13.2% | 0% | 9% | 1% | 0% | 5% | 0% | 10% | 25% | 10% |
| | 50-year, +30% cement | None | 4% | 14.3% | 0% | 10% | 1% | 0% | 5% | 0% | 10% | 25% | 10% |
| | 50-year, +40% cement | None | 4% | 15.4% | 0% | 10% | 1% | 0% | 5% | 0% | 10% | 25% | 10% |
| | 50-year, +50% cement | None | 4% | 16.5% | 0% | 10% | 1% | 0% | 5% | 0% | 10% | 25% | 10% |
| | 25% repair every 20-years | None | 4% | 11% | 0% | 9% | 0% | 0% | 5% | 0% | 10% | 25% | 10% |
| | 50% repair evey 20-years | None | 4% | 11% | 0% | 4% | 0% | 0% | 0% | 0% | 11% | 22% | 15% |
| Thermal Energy Decarbonization | 33.3-year, +10% cement | 18% Thermal Reduction | 4% | 12.1% | 0% | 4% | 0% | 0% | 0% | 0% | 12% | 24% | 16% |
| | 33.3-year, +20% cement | 18% Thermal Reduction | 4% | 13.2% | 0% | 5% | 1% | 0% | 0% | 0% | 12% | 24% | 16% |
| | 33.3-year, +30% cement | 18% Thermal Reduction | 4% | 14.3% | 0% | 5% | 1% | 0% | 0% | 0% | 12% | 24% | 16% |
| | 33.3-year, +40% cement | 18% Thermal Reduction | 4% | 15.4% | 0% | 5% | 1% | 0% | 0% | 0% | 12% | 24% | 16% |
| | 33.3-year, +50% cement | 18% Thermal Reduction | 4% | 16.5% | 0% | 5% | 1% | 0% | 0% | 0% | 12% | 24% | 16% |
| | 50-year, +10% cement | 18% Thermal Reduction | 4% | 12.1% | 0% | 10% | 0% | 0% | 6% | 0% | 11% | 27% | 11% |
| | 50-year, +20% cement | 18% Thermal Reduction | 4% | 13.2% | 0% | 10% | 0% | 0% | 6% | 0% | 11% | 27% | 11% |
| | 50-year, +30% cement | 18% Thermal Reduction | 4% | 14.3% | 0% | 10% | 1% | 0% | 6% | 0% | 11% | 27% | 11% |
| | 50-year, +40% cement | 18% Thermal Reduction | 4% | 15.4% | 0% | 10% | 1% | 0% | 6% | 0% | 11% | 27% | 11% |
| | 50-year, +50% cement | 18% Thermal Reduction | 4% | 16.5% | 0% | 11% | 1% | 0% | 6% | 0% | 11% | 27% | 11% |
| | 25% repair every 20-years | 18% Thermal Reduction | 4% | 11% | 0% | 10% | 0% | 0% | 6% | 0% | 11% | 27% | 11% |
| | 50% repair evey 20-years | 18% Thermal Reduction | 4% | 11% | 0% | 4% | 0% | 0% | 0% | 0% | 12% | 24% | 16% |
| Limestone Addition | 33.3-year, +10% cement | None | 15% | 12.1% | 0% | 4% | 1% | 0% | 0% | 0% | 11% | 22% | 15% |
| | 33.3-year, +20% cement | None | 15% | 13.2% | 0% | 5% | 1% | 0% | 0% | 0% | 11% | 22% | 15% |
| | 33.3-year, +30% cement | None | 15% | 14.3% | 0% | 5% | 1% | 0% | 1% | 0% | 11% | 22% | 15% |
| | 33.3-year, +40% cement | None | 15% | 15.4% | 0% | 5% | 1% | 0% | 1% | 0% | 11% | 22% | 15% |
| | 33.3-year, +50% cement | None | 15% | 16.5% | 0% | 5% | 1% | 0% | 1% | 0% | 11% | 22% | 15% |
| | 50-year, +10% cement | None | 15% | 12.1% | 0% | 9% | 0% | 0% | 5% | 0% | 10% | 25% | 10% |
| | 50-year, +20% cement | None | 15% | 13.2% | 0% | 9% | 1% | 0% | 5% | 0% | 10% | 25% | 10% |
| | 50-year, +30% cement | None | 15% | 14.3% | 0% | 10% | 1% | 0% | 5% | 0% | 10% | 25% | 10% |
| | 50-year, +40% cement | None | 15% | 15.4% | 0% | 10% | 1% | 0% | 5% | 0% | 10% | 25% | 10% |
| | 50-year, +50% cement | None | 15% | 16.5% | 0% | 10% | 1% | 0% | 5% | 0% | 10% | 25% | 10% |
| | 25% repair every 20-years | None | 15% | 11% | 0% | 9% | 0% | 0% | 5% | 0% | 10% | 25% | 10% |
| | 50% repair evey 20-years | None | 15% | 11% | 0% | 4% | 0% | 0% | 0% | 0% | 11% | 22% | 15% |
| Limestone Addition + Thermal Energy Decarbonization | 33.3-year, +10% cement | 18% Thermal Reduction | 15% | 12.1% | 0% | 4% | 0% | 0% | 0% | 0% | 12% | 24% | 16% |
| | 33.3-year, +20% cement | 18% Thermal Reduction | 15% | 13.2% | 0% | 5% | 1% | 0% | 0% | 0% | 12% | 24% | 16% |
| | 33.3-year, +30% cement | 18% Thermal Reduction | 15% | 14.3% | 0% | 5% | 1% | 0% | 1% | 0% | 12% | 24% | 16% |
| | 33.3-year, +40% cement | 18% Thermal Reduction | 15% | 15.4% | 0% | 5% | 1% | 0% | 1% | 0% | 12% | 24% | 16% |
| | 33.3-year, +50% cement | 18% Thermal Reduction | 15% | 16.5% | 0% | 5% | 1% | 0% | 1% | 0% | 12% | 24% | 16% |
| | 50-year, +10% cement | 18% Thermal Reduction | 15% | 12.1% | 0% | 10% | 0% | 0% | 6% | 0% | 10% | 27% | 11% |
| | 50-year, +20% cement | 18% Thermal Reduction | 15% | 13.2% | 0% | 10% | 0% | 0% | 6% | 0% | 10% | 27% | 11% |
| | 50-year, +30% cement | 18% Thermal Reduction | 15% | 14.3% | 0% | 10% | 1% | 0% | 6% | 0% | 10% | 27% | 11% |
| | 50-year, +40% cement | 18% Thermal Reduction | 15% | 15.4% | 0% | 10% | 1% | 0% | 6% | 0% | 10% | 27% | 11% |
| | 50-year, +50% cement | 18% Thermal Reduction | 15% | 16.5% | 0% | 11% | 1% | 0% | 6% | 0% | 10% | 27% | 11% |
| | 25% repair every 20-years | 18% Thermal Reduction | 15% | 11% | 0% | 10% | 0% | 0% | 6% | 0% | 10% | 27% | 11% |
| | 50% repair evey 20-years | 18% Thermal Reduction | 15% | 11% | 0% | 5% | 0% | 0% | 0% | 0% | 12% | 24% | 16% |
| EU Limestone Addition + Complete Energy Decarbonization | 50-year, +10% cement | 100% Decarbonation | 35% | 12.1% | 0% | 21% | 0% | 0% | 18% | 0% | 20% | 62% | 23% |
| | 50-year, +20% cement | 100% Decarbonation | 35% | 13.2% | 0% | 21% | 0% | 0% | 18% | 0% | 20% | 62% | 23% |
| | 50-year, +30% cement | 100% Decarbonation | 35% | 14.3% | 0% | 22% | 0% | 0% | 18% | 0% | 20% | 62% | 23% |
| | 50-year, +40% cement | 100% Decarbonation | 35% | 15.4% | 0% | 22% | 0% | 0% | 18% | 0% | 20% | 62% | 23% |
| | 50-year, +50% cement | 100% Decarbonation | 35% | 16.5% | 0% | 22% | 0% | 0% | 19% | 0% | 20% | 62% | 23% |
| | 25% repair every 20-years | 100% Decarbonation | 35% | 11% | 0% | 21% | 0% | 0% | 18% | 0% | 20% | 62% | 23% |

*Table 7.2: Sensitivity analysis – percentage error for T. Carb and overlapping*

## 7.4 Life Extension

Figure 7.1 and 7.8 show the results of maximum, minimum and median additive carbon dioxide emissions associated with avoidance through life extension. The results also highlight the potential error for each as explained in Section 7.2 and are illustrated with the error bars in the graphs. The additive carbon dioxide emissions for each type of application and concrete strength are presented in Figure 7.2 through 7.7 and Figure 7.9 through 7.14 for a 33.3 and 50-year service life, respectively. The variables of each scenario are: Cement Content (%); Limestone Content (%); Service Life (years); $CO_2$ uptake limit (ie. T. Carb value expressed as a %); Thermal Decarbonization (%); and Total Energy Decarbonization (including electrical energy expressed as a %) are included in the radar graphs through the end of Section 7.8.

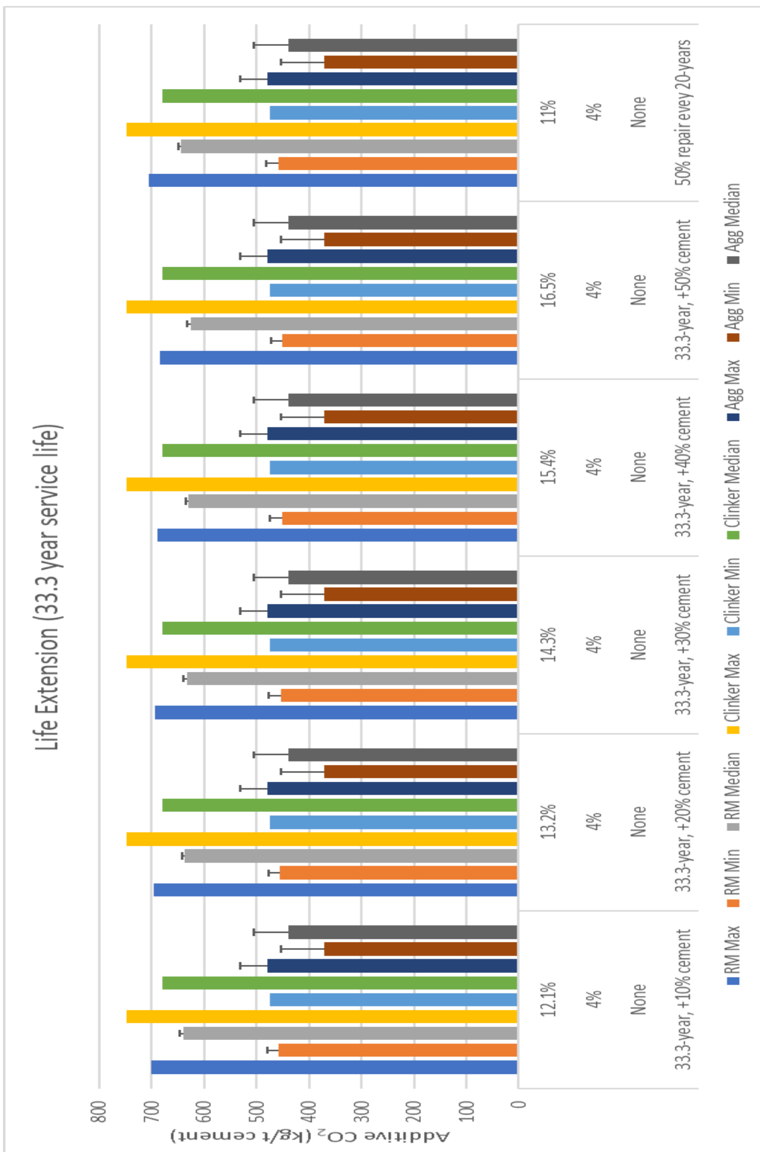


*Figure 7.1: Life Extension – 33.3 year service life*

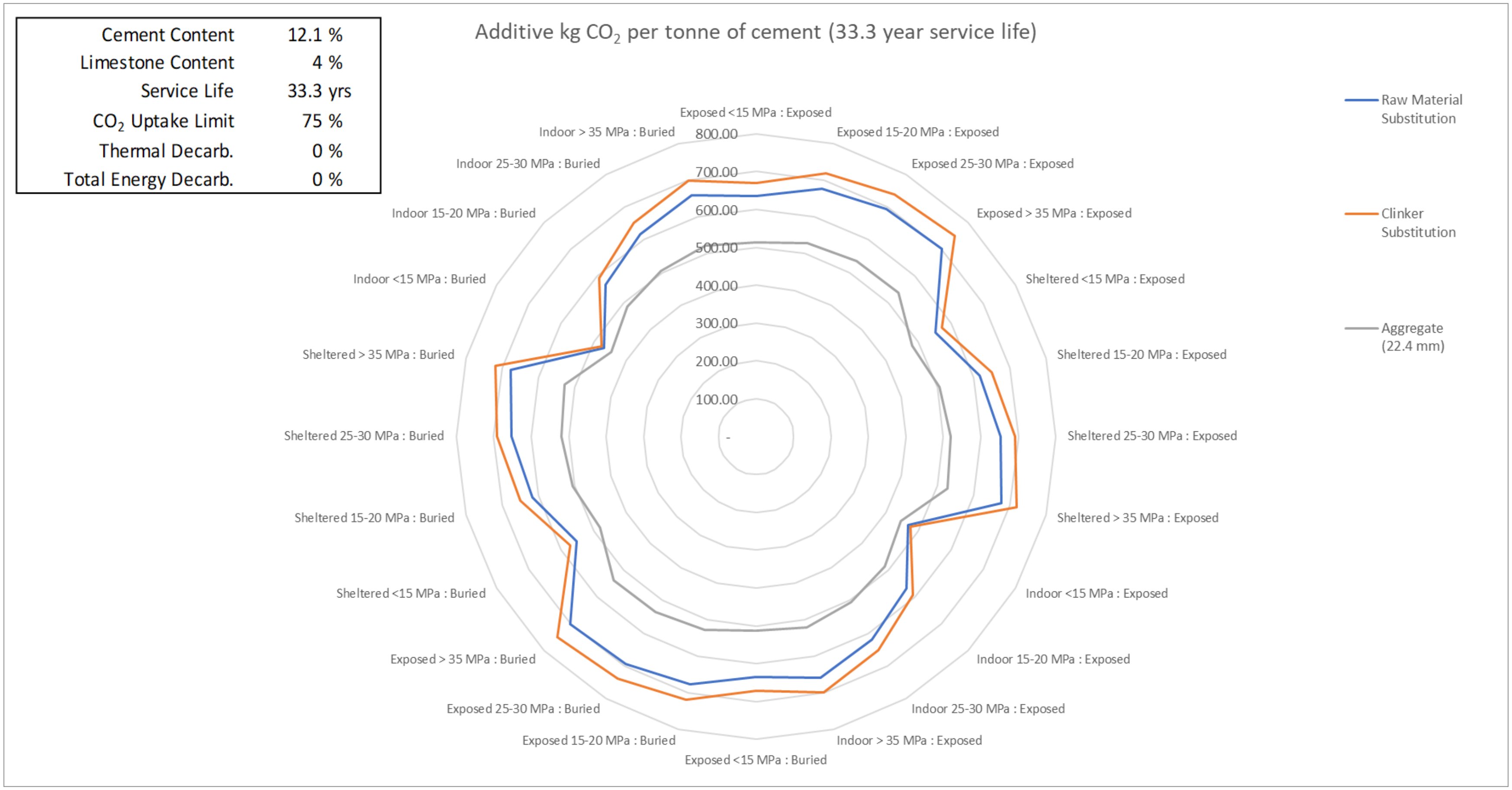


*Figure 7.2: Life Extension – 33.3 year service life*

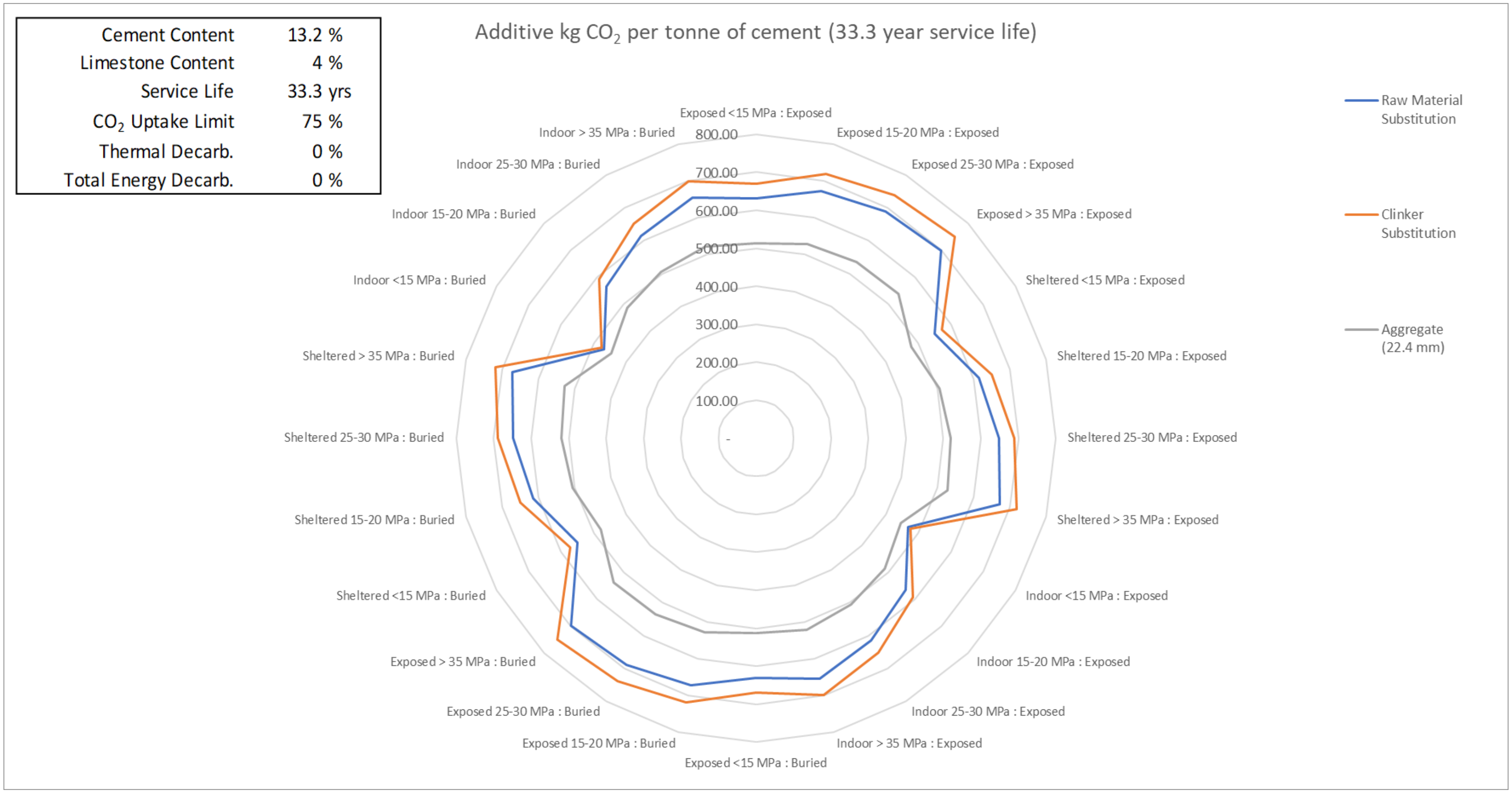


*Figure 7.3: Life Extension – 33.3 year service life*

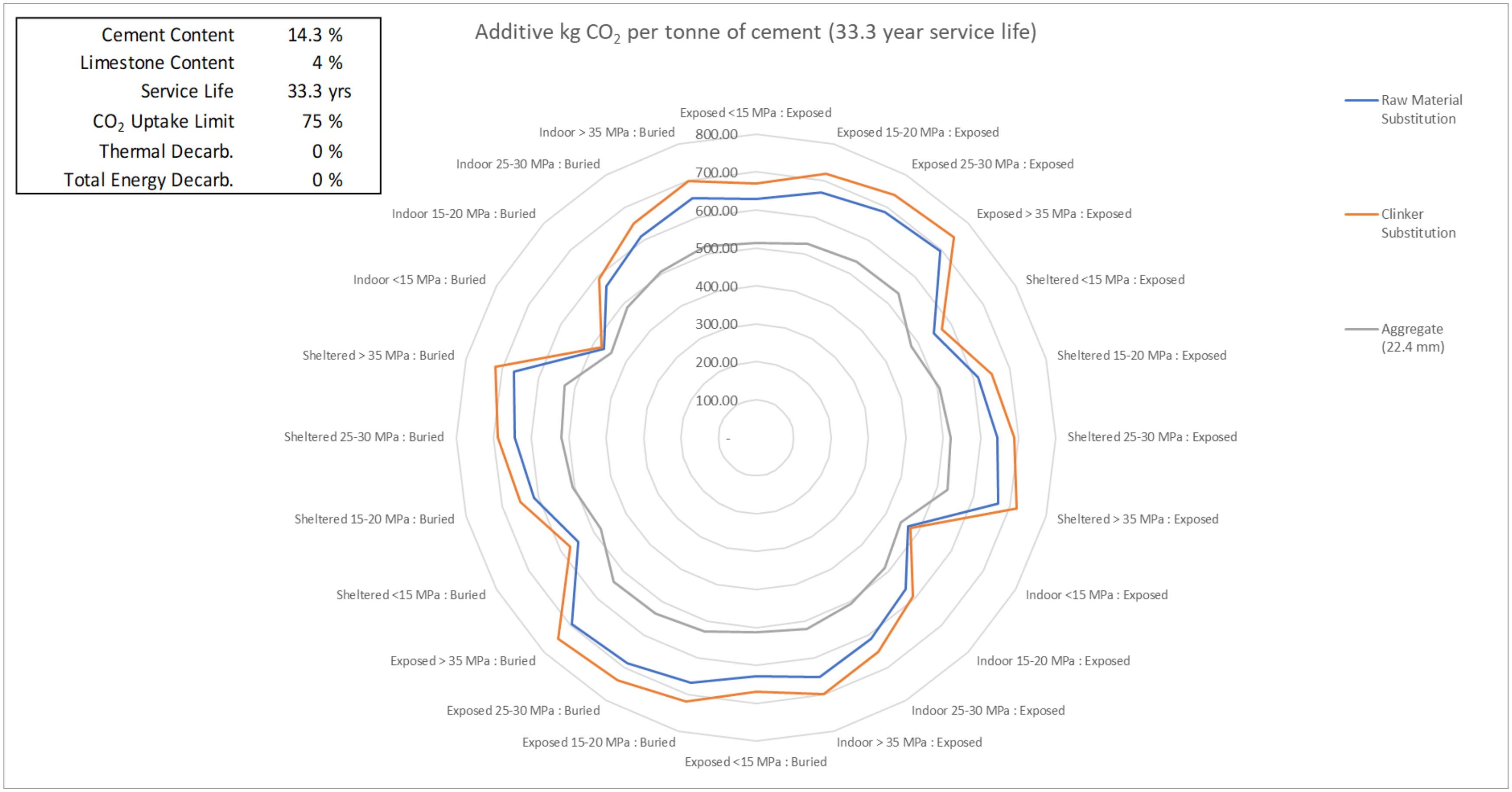


*Figure 7.4: Life Extension – 33.3 year service life*

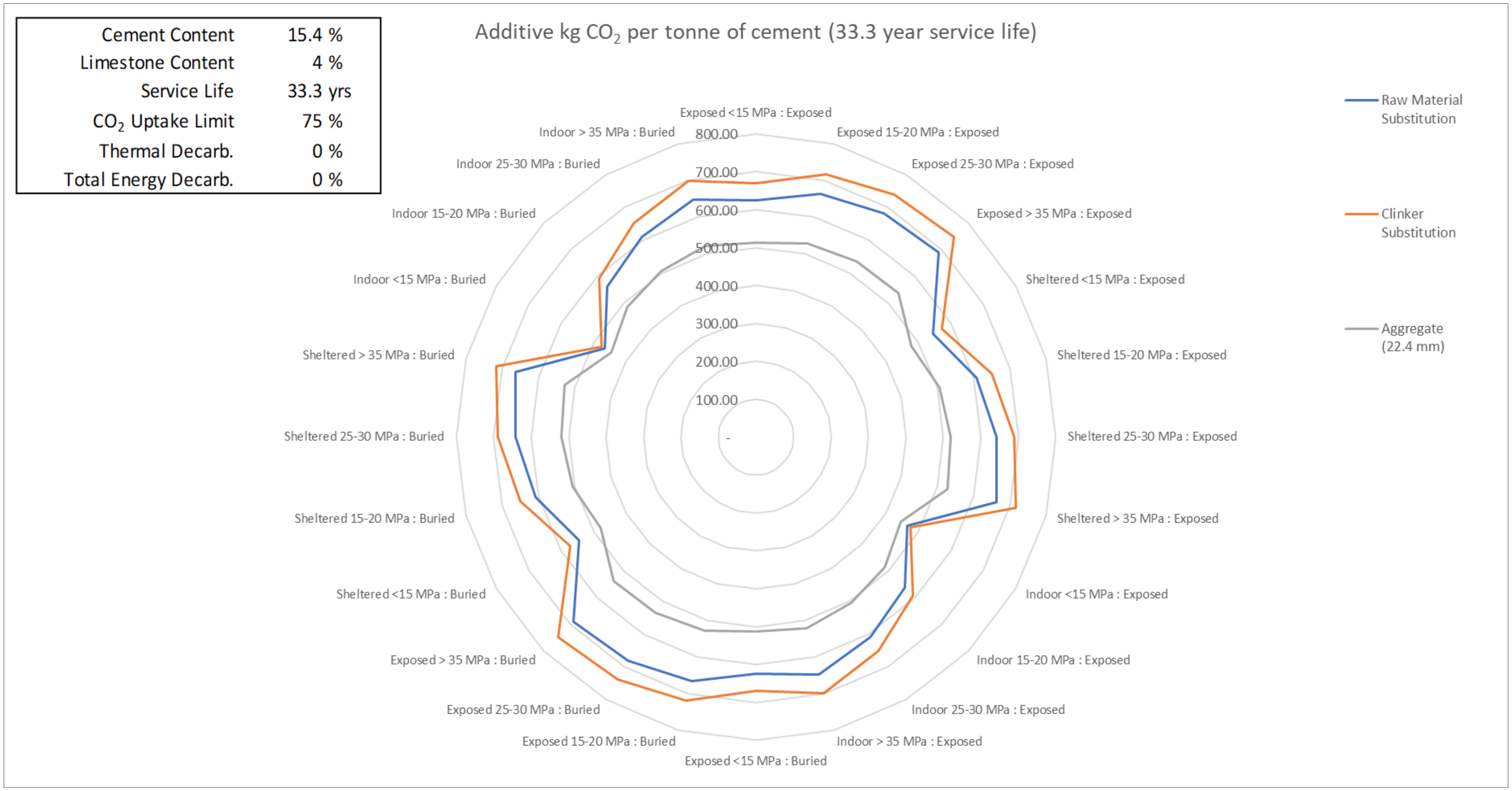


*Figure 7.5: Life Extension – 33.3 year service life*

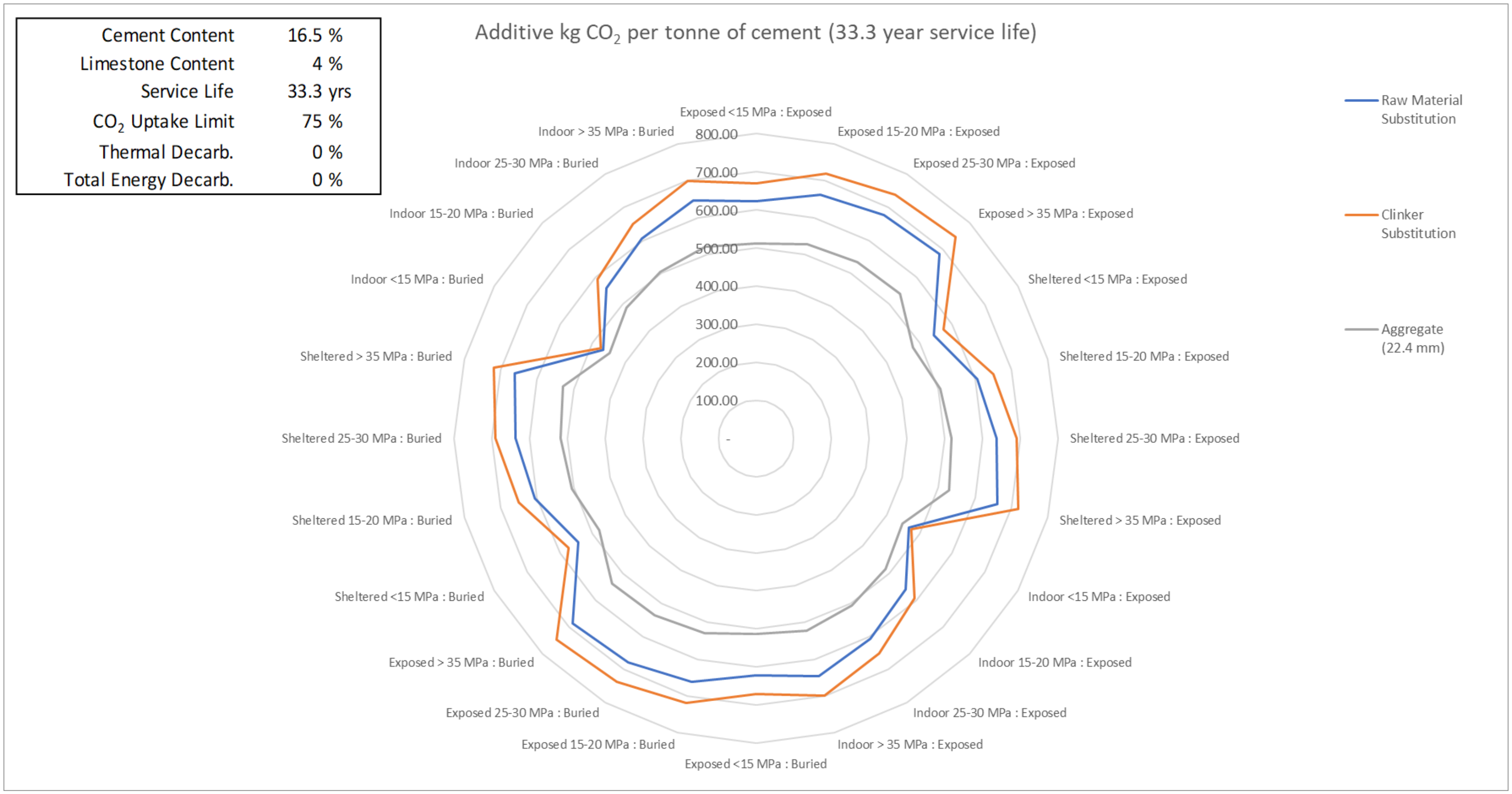


*Figure 7.6: Life Extension – 33.3 year service life*

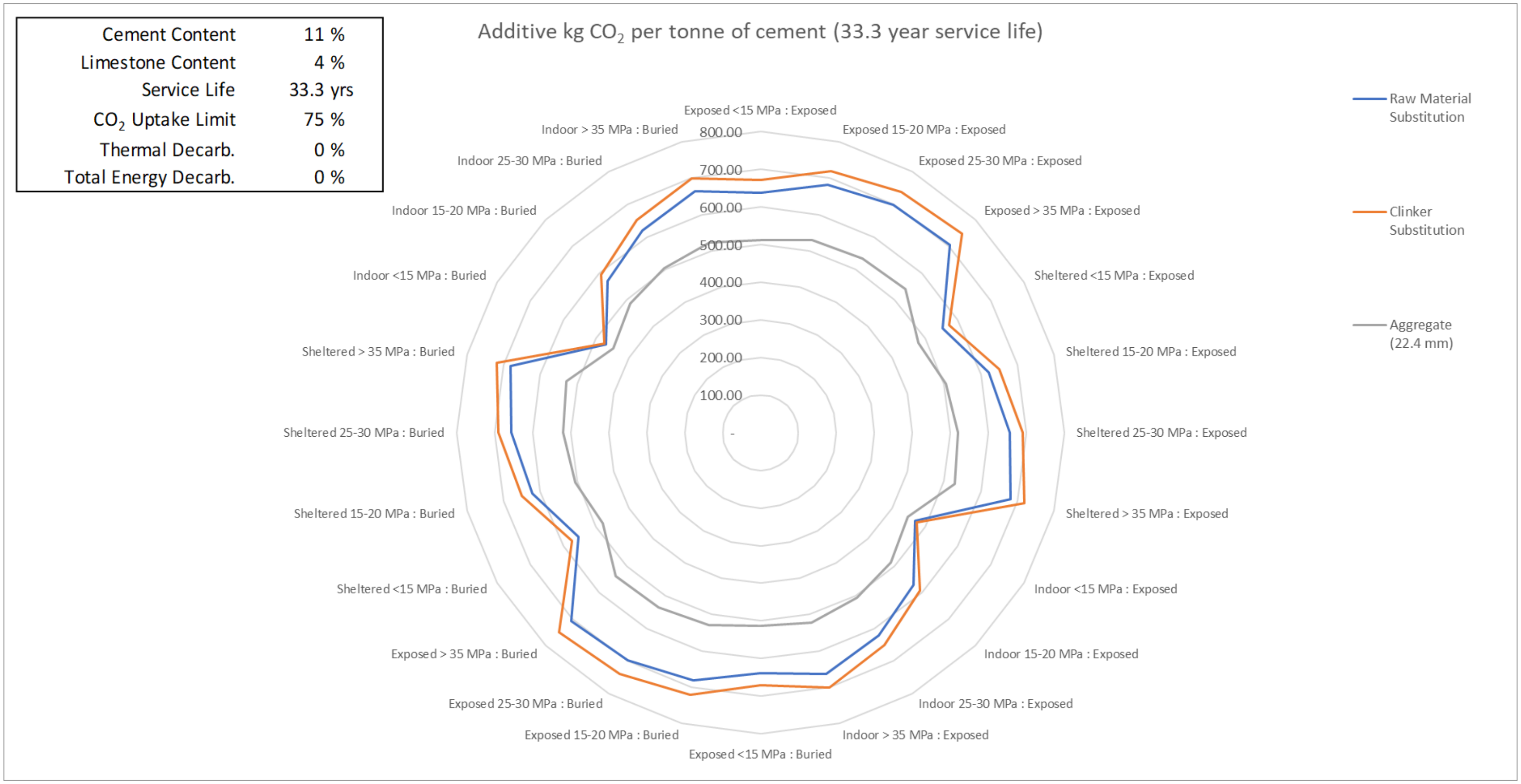


*Figure 7.7: Life Extension – 33.3 year service life*

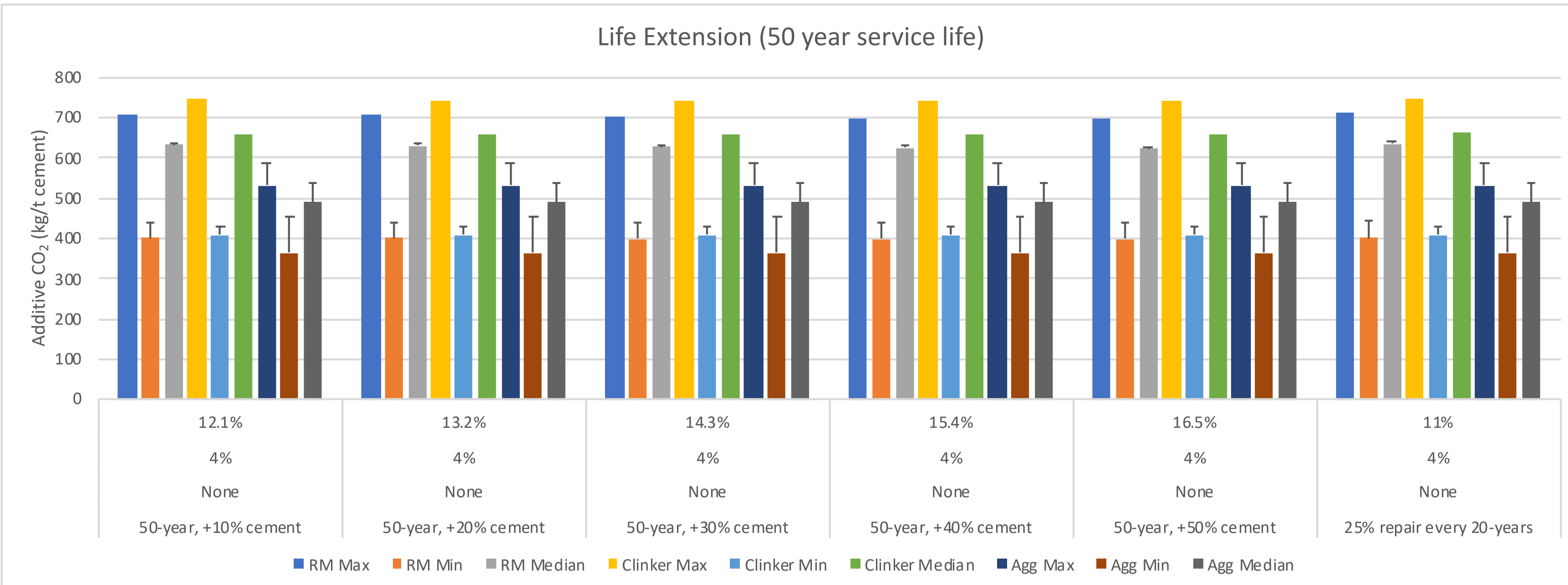


*Figure 7.8: Life Extension – 50 year service life*

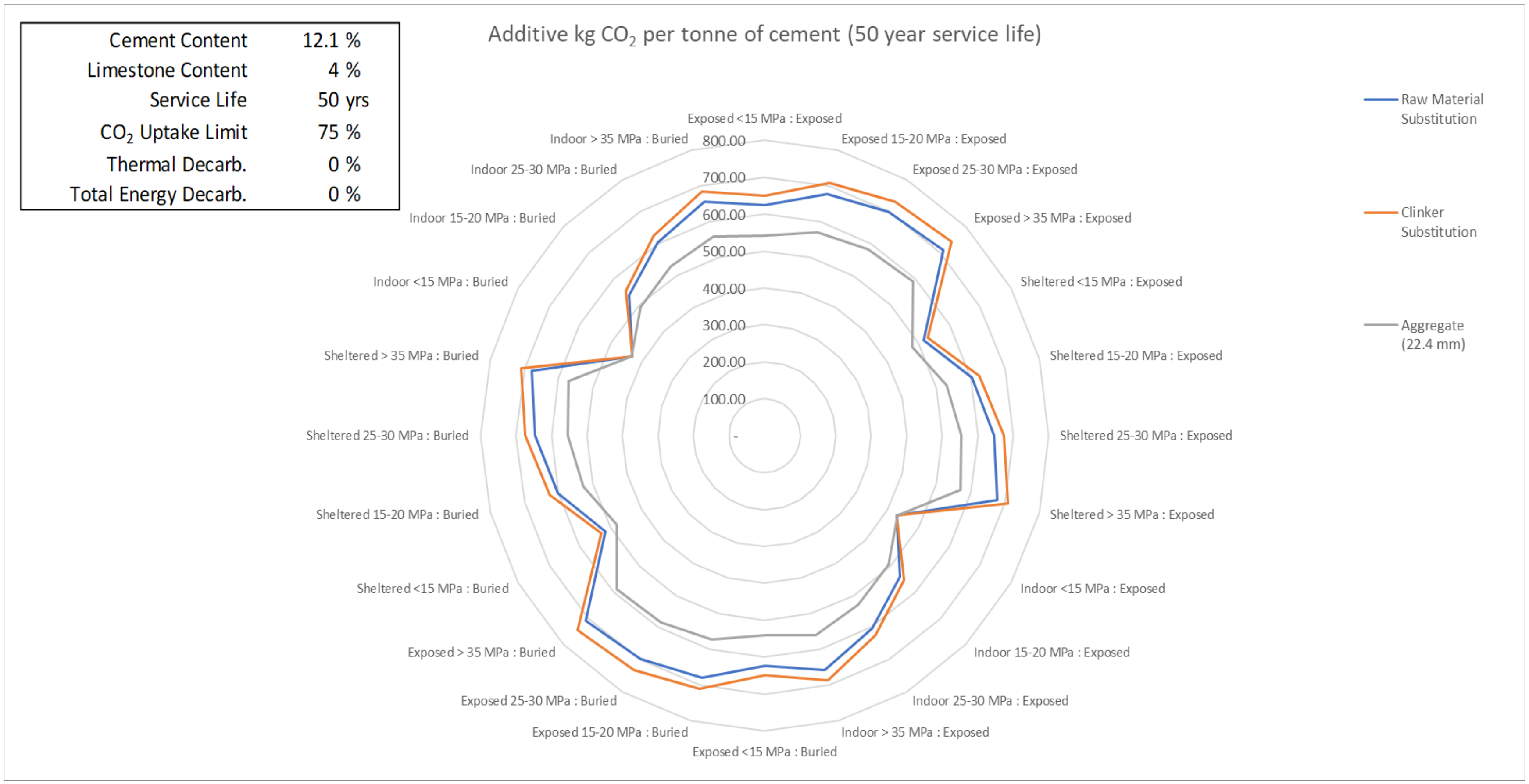


*Figure 7.9: Life Extension – 50 year service life*

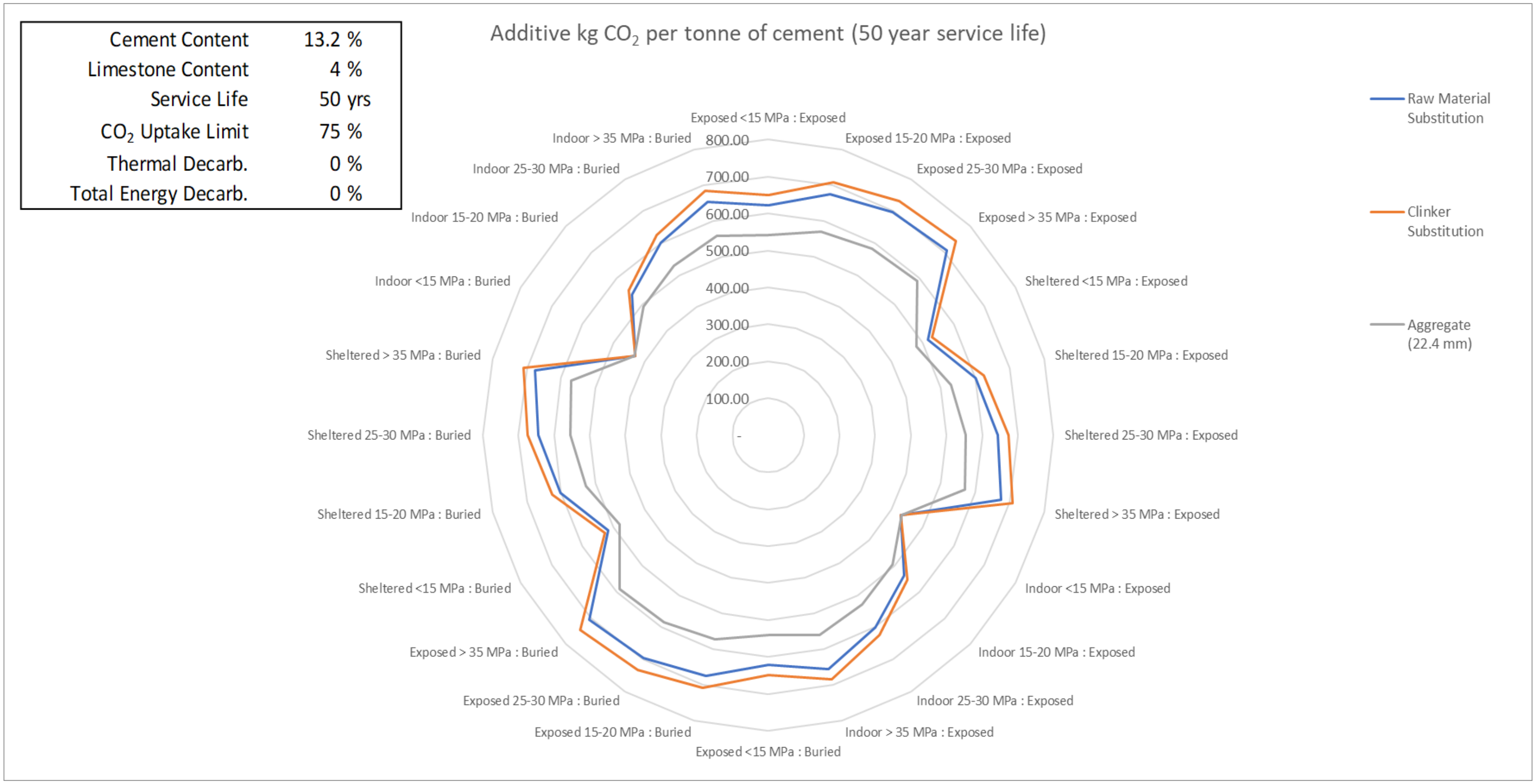


*Figure 7.10: Life Extension – 50 year service life*

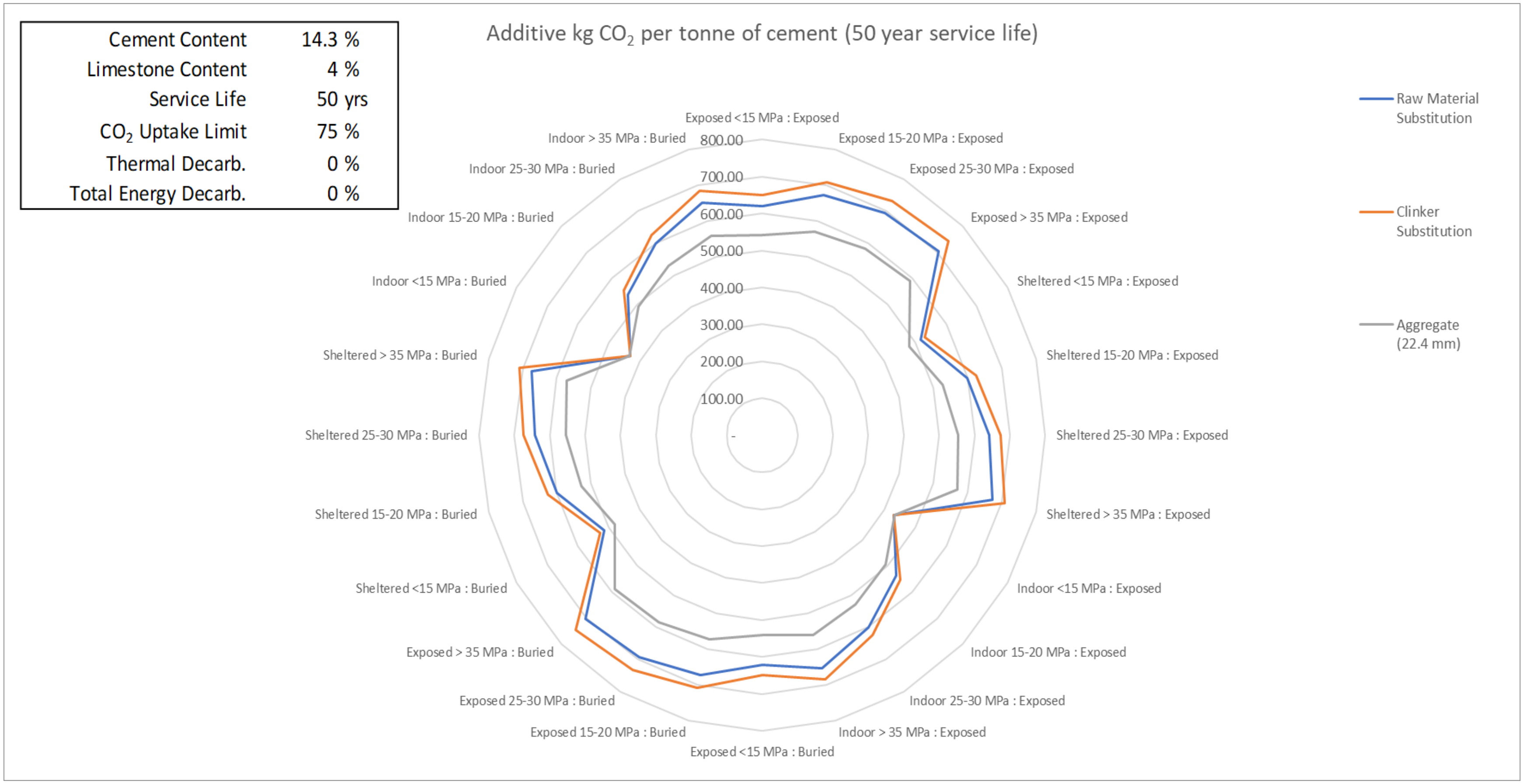


*Figure 7.11: Life Extension – 50 year service life*

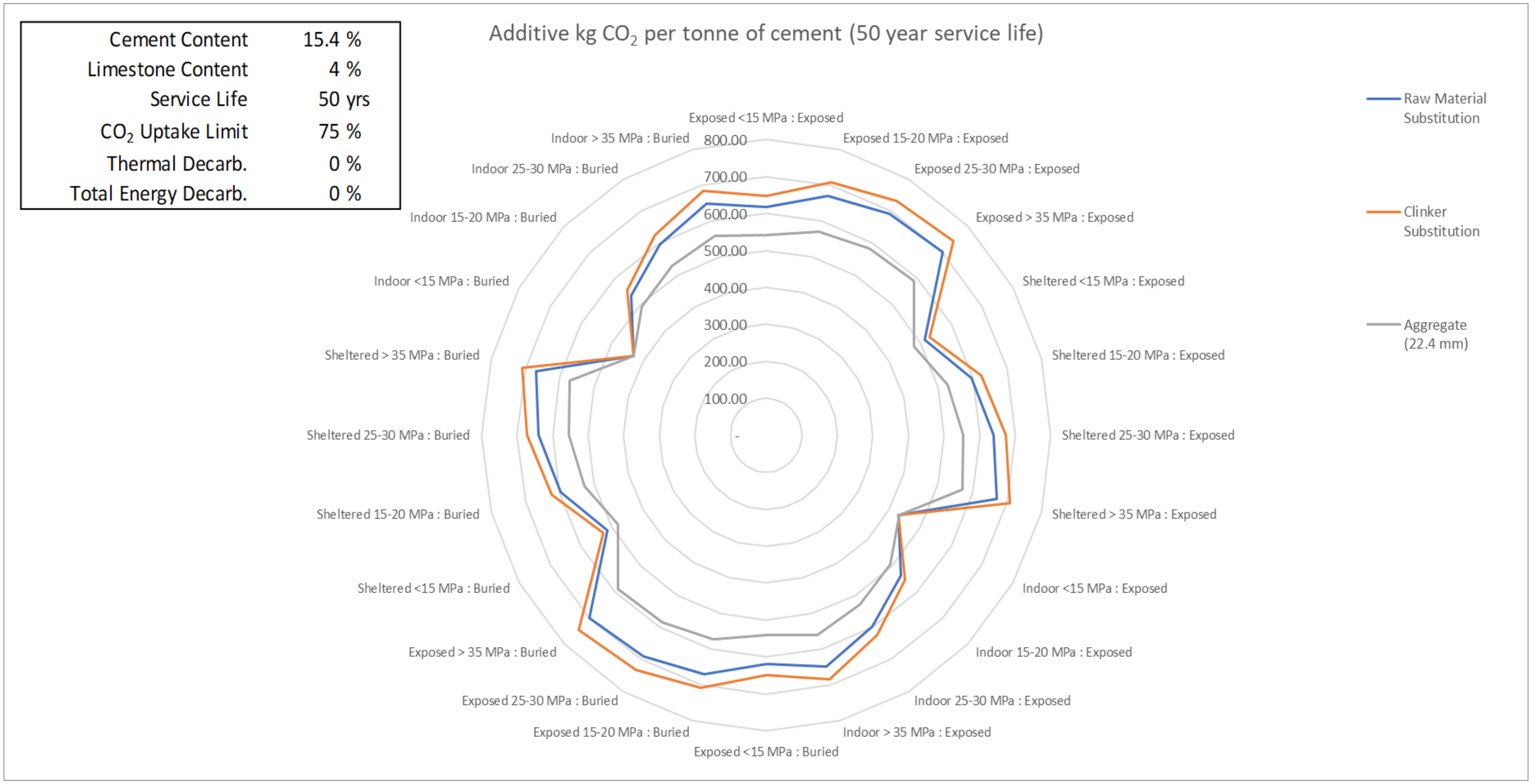


*Figure 7.12: Life Extension – 50 year service life*

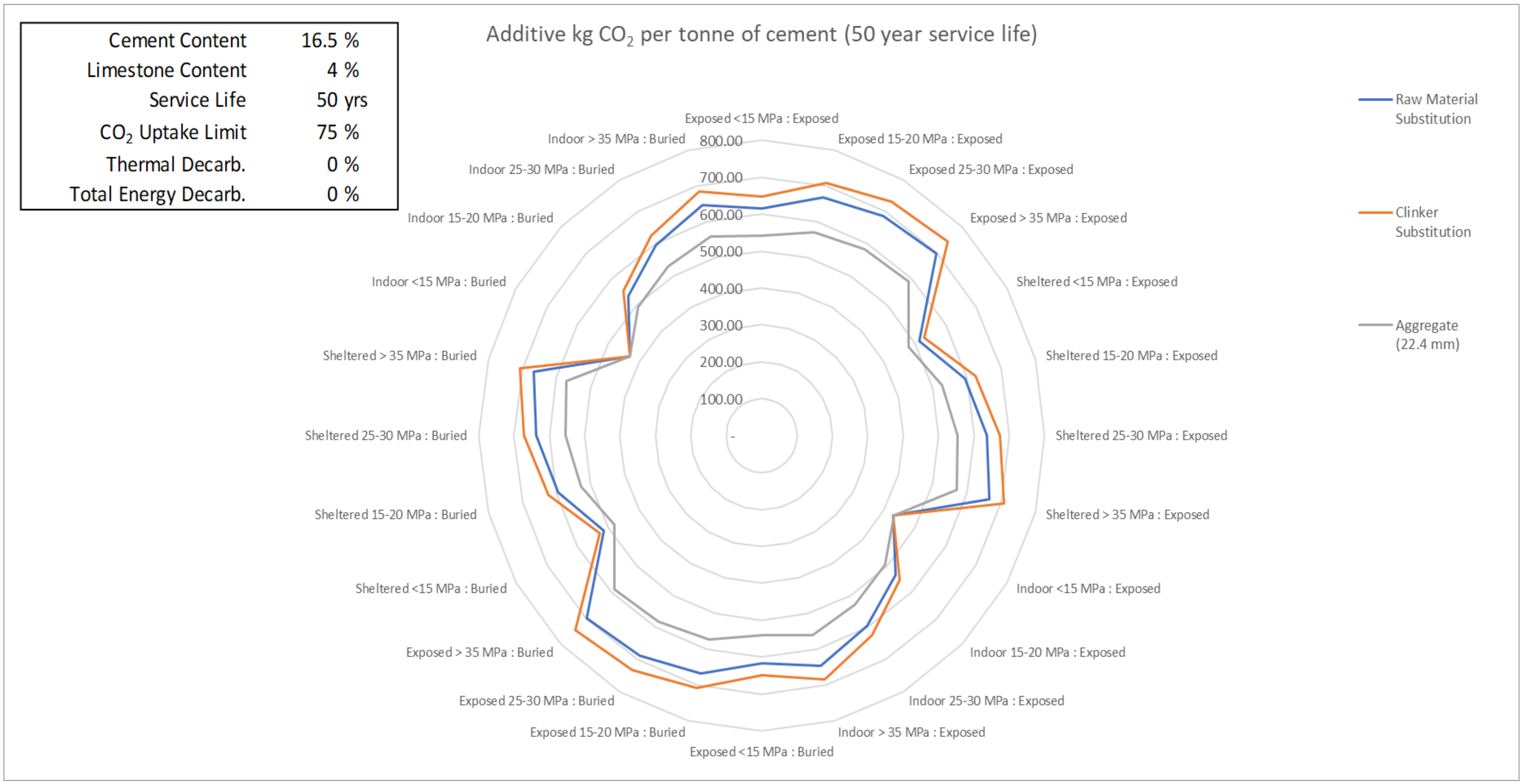


*Figure 7.13: Life Extension – 50 year service life*

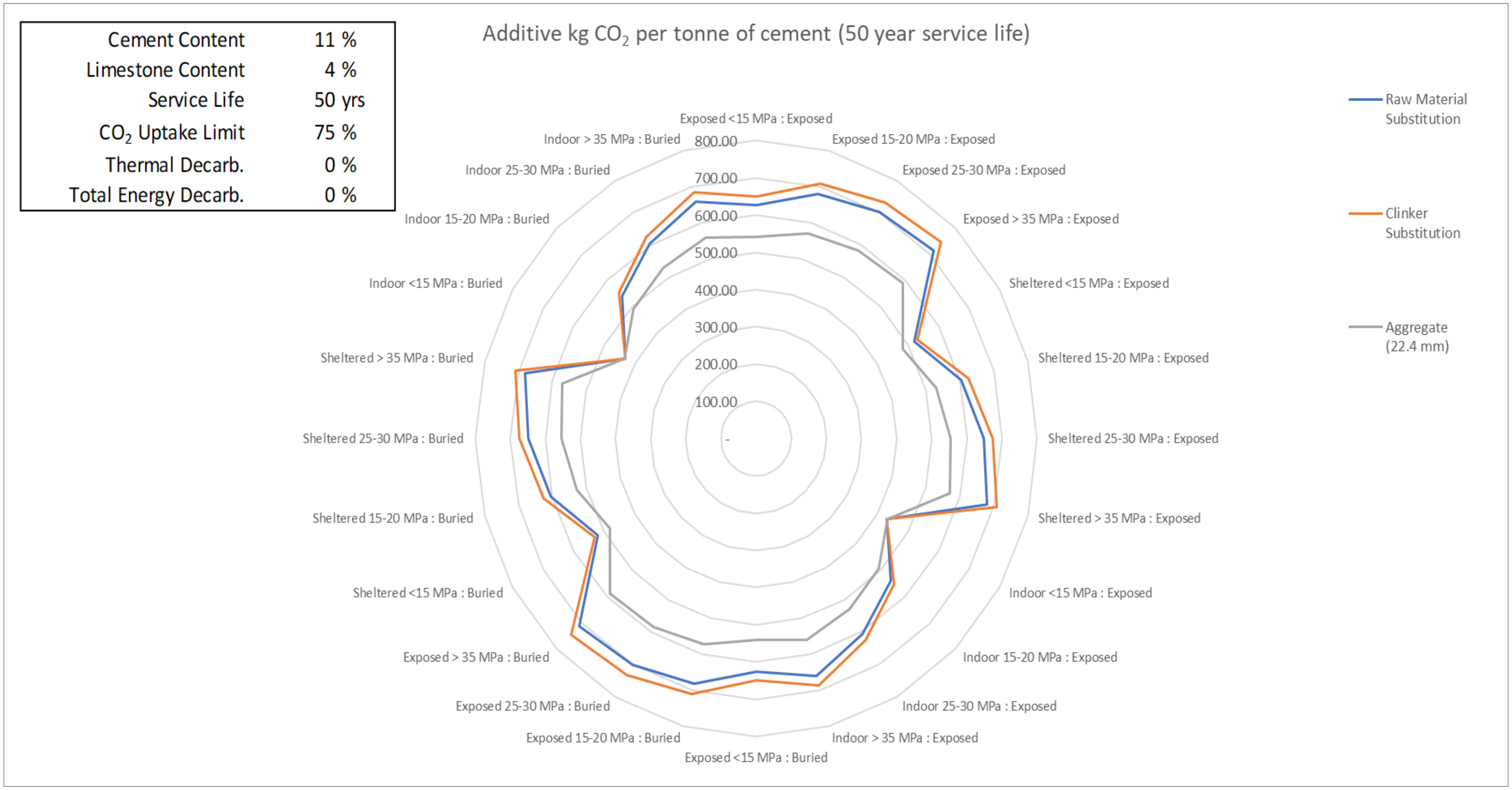


*Figure 7.14: Life Extension – 50 year service life*

### 7.4.1 Results and Interpretation of Life Extension Scenarios

The Life Extension Scenarios show that carbon dioxide uptake plays a major role in lowering the additive $CO_2$/t cement. Carbon dioxide uptake has a significant benefit as is clearly visible in all of the radar graphs. This is especially apparent in indoor use concrete that is less than 15 MPa which has the fastest carbon dioxide uptake rate. As expected, longer service life leads to similar results regardless of secondary use as maximum carbon dioxide uptake is reached. Secondary use as aggregates results in the lowest additive $CO_2$/t cement emissions as expected for all scenarios due to the continued $CO_2$ uptake by aggregates during the secondary use.

Life extension is a valid approach for the Canadian cement industry to reduce additive $CO_2$ emissions.

## 7.5 Thermal Energy Decarbonization

Figure 7.15 and 7.22 show the results of maximum, minimum and median additive carbon dioxide emissions associated with avoidance through thermal energy decarbonization based on a reduction equivalent to reaching the levels of the Germany cement industry. The results also highlight the potential error for each scenario as mentioned in Section 7.3 and are illustrated with the error bars in the graphs. The additive carbon dioxide emissions for each type of application and concrete strength as detailed in Section 7.2 are presented in Figures 7.16 through 7.21 and Figures 7.23 through 7.28 for a 33.3 and 50-year service life, respectively.

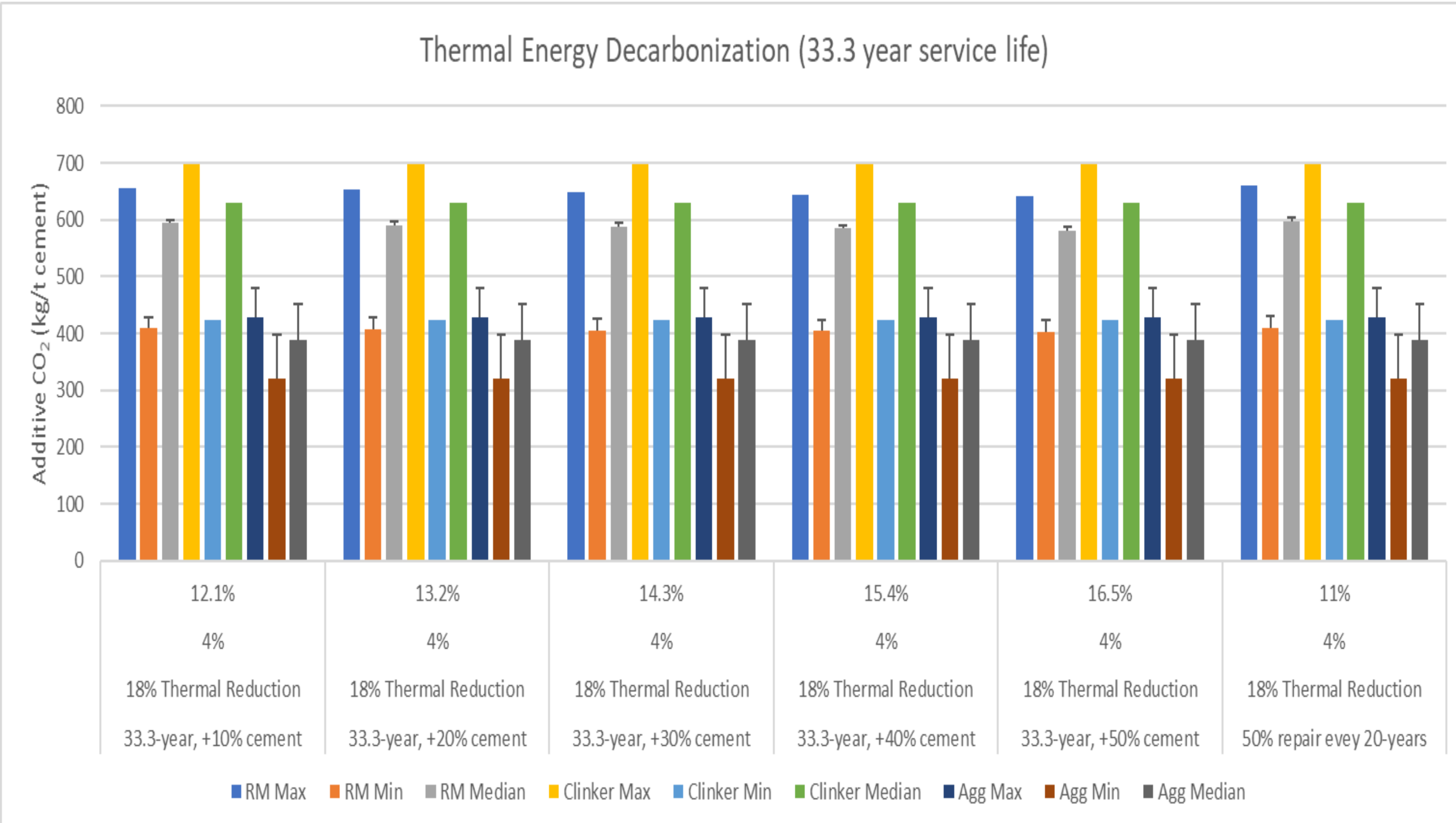


*Figure 7.15: Thermal Energy Decarbonization – 33.3 year service life*

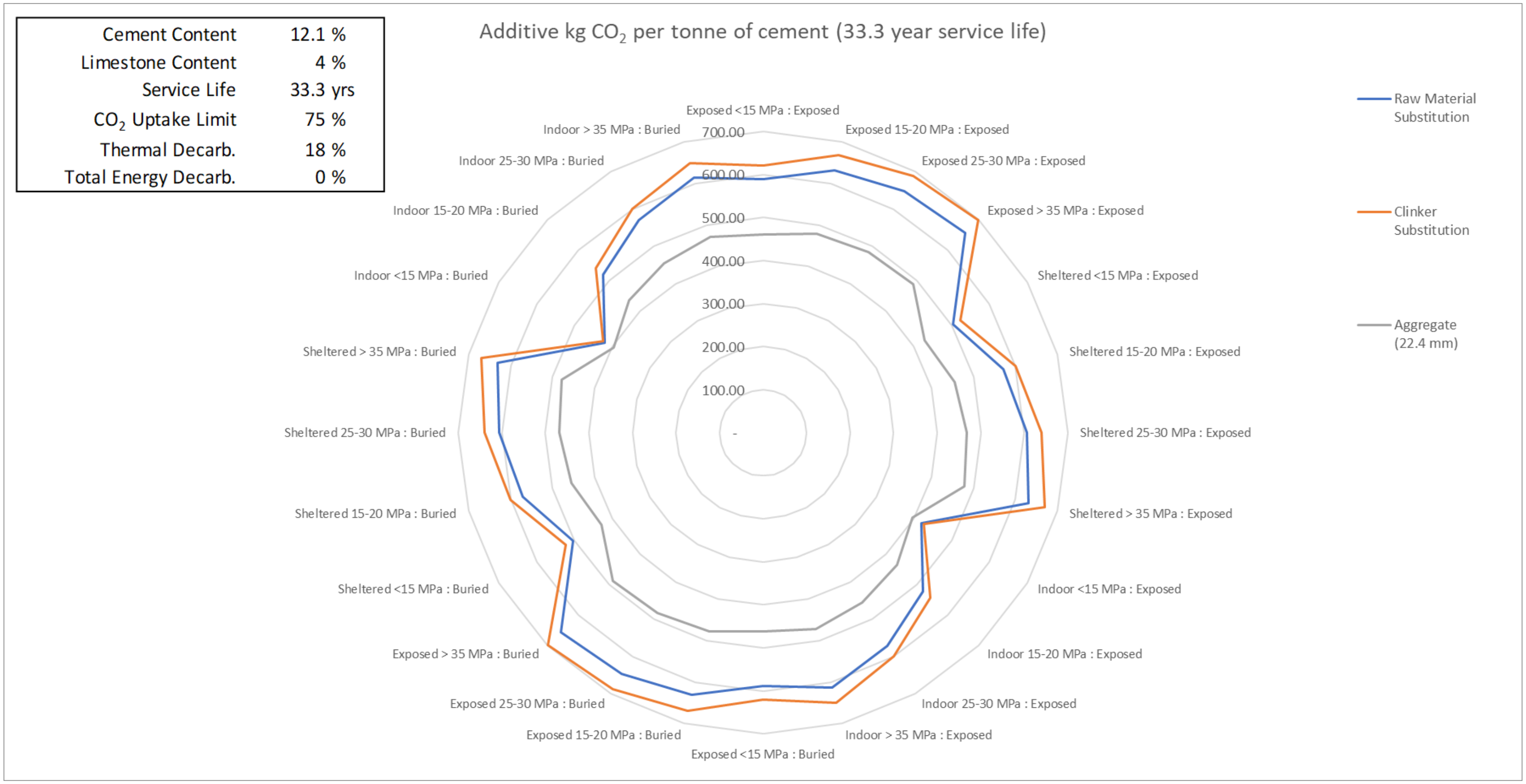


*Figure 7.16: Thermal Energy Decarbonization – 33.3 year service life*

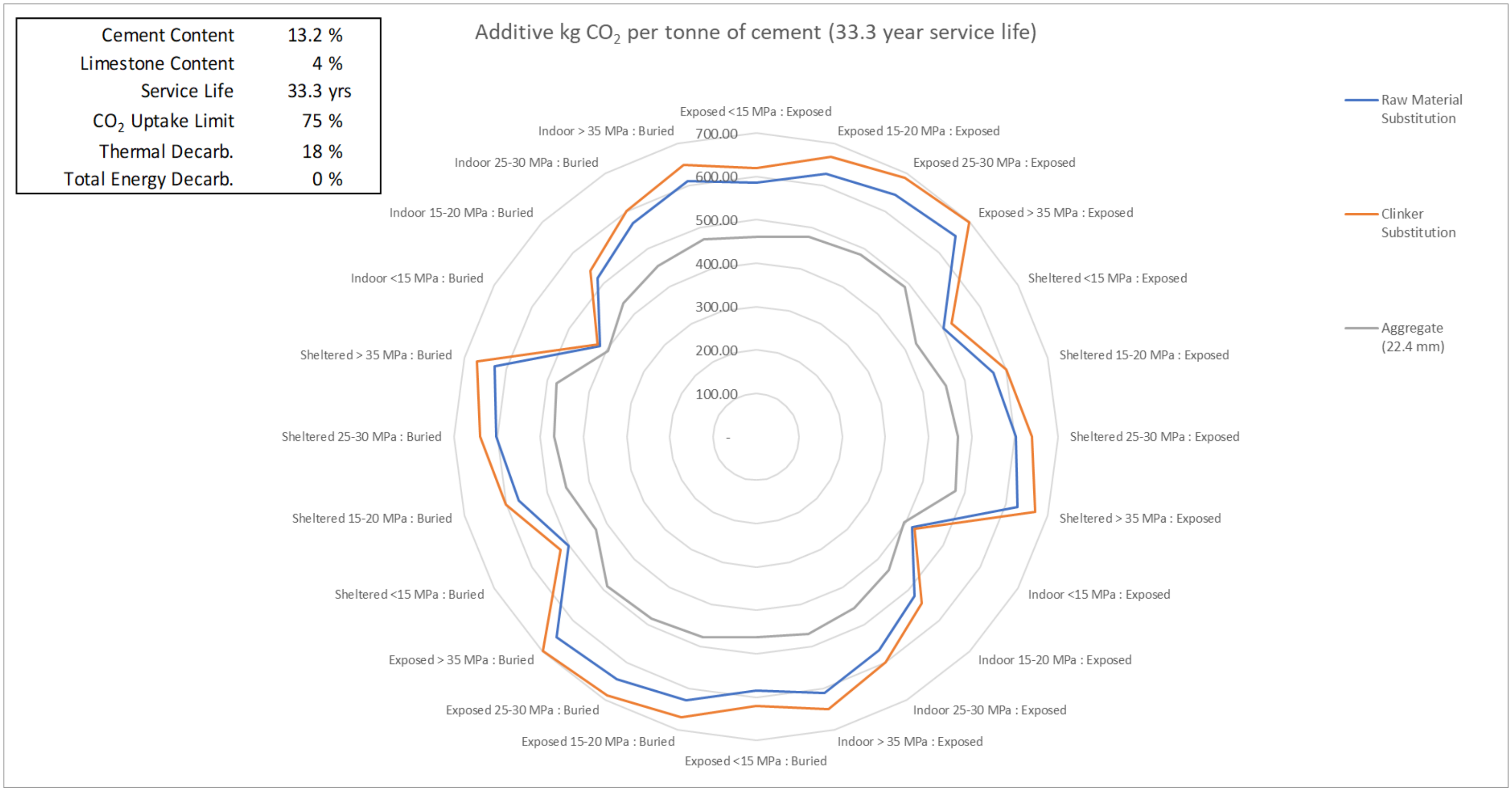


*Figure 7.17: Thermal Energy Decarbonization – 33.3 year service life*

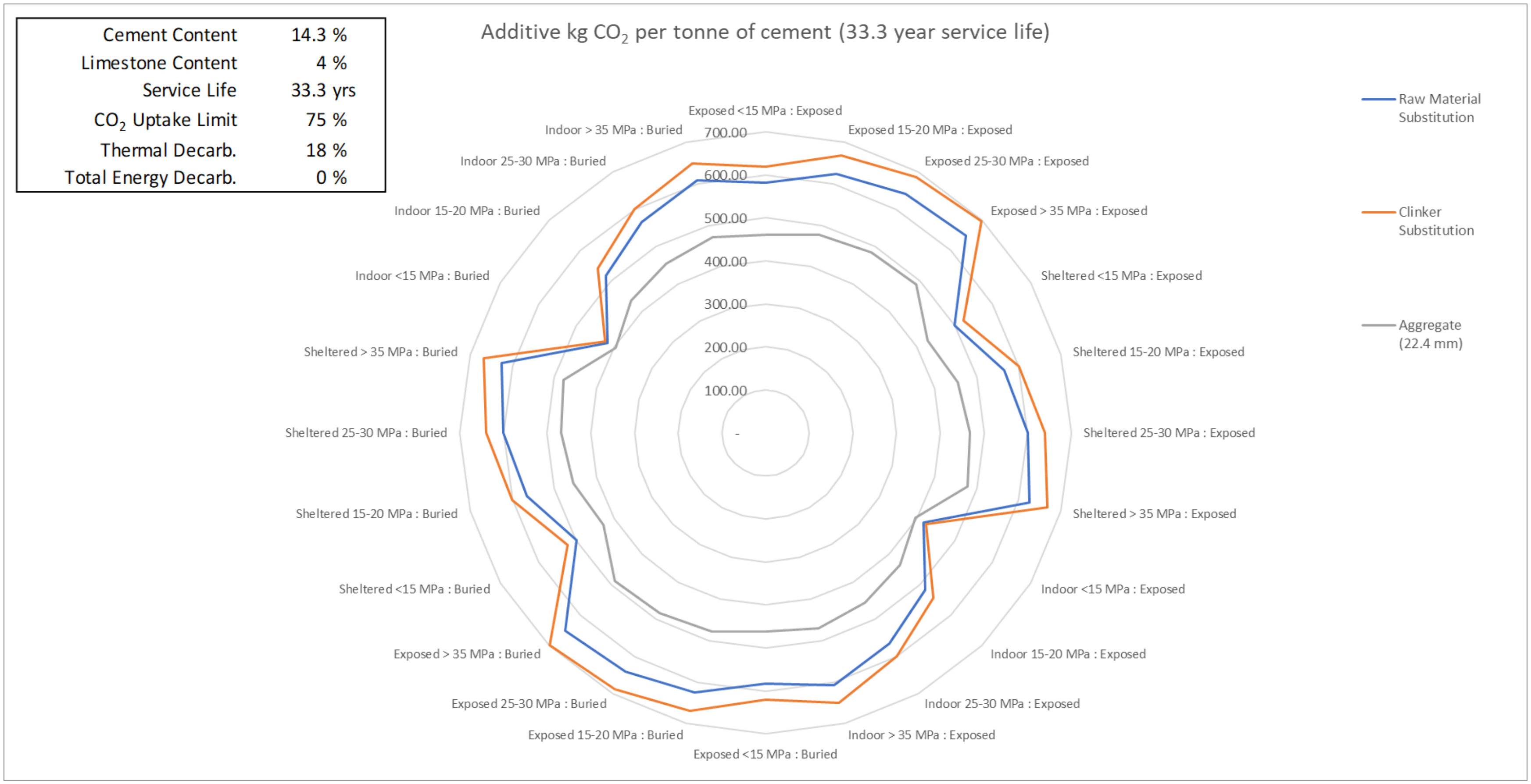


*Figure 7.18: Thermal Energy Decarbonization – 33.3 year service life*

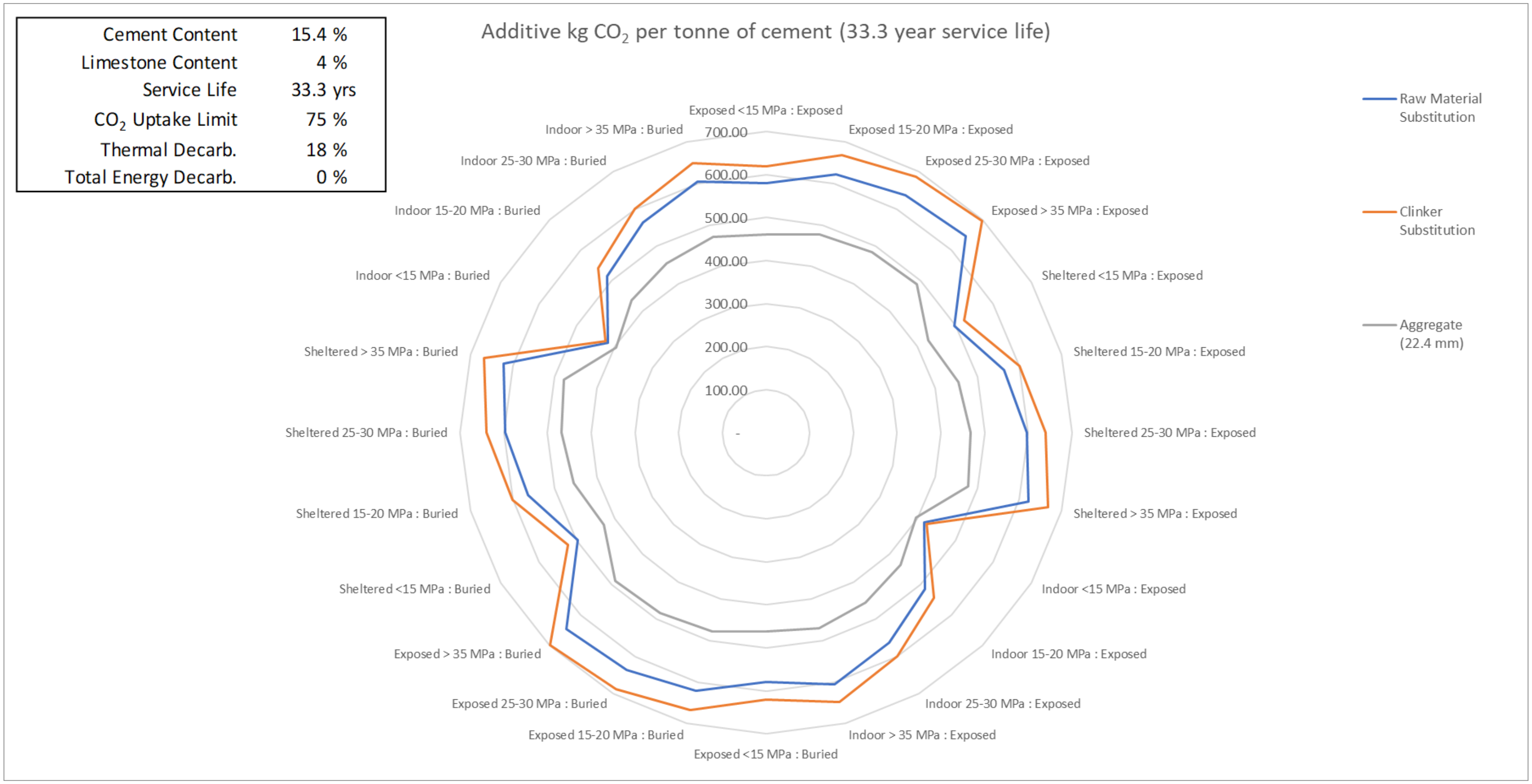


*Figure 7.19: Thermal Energy Decarbonization – 33.3 year service life*

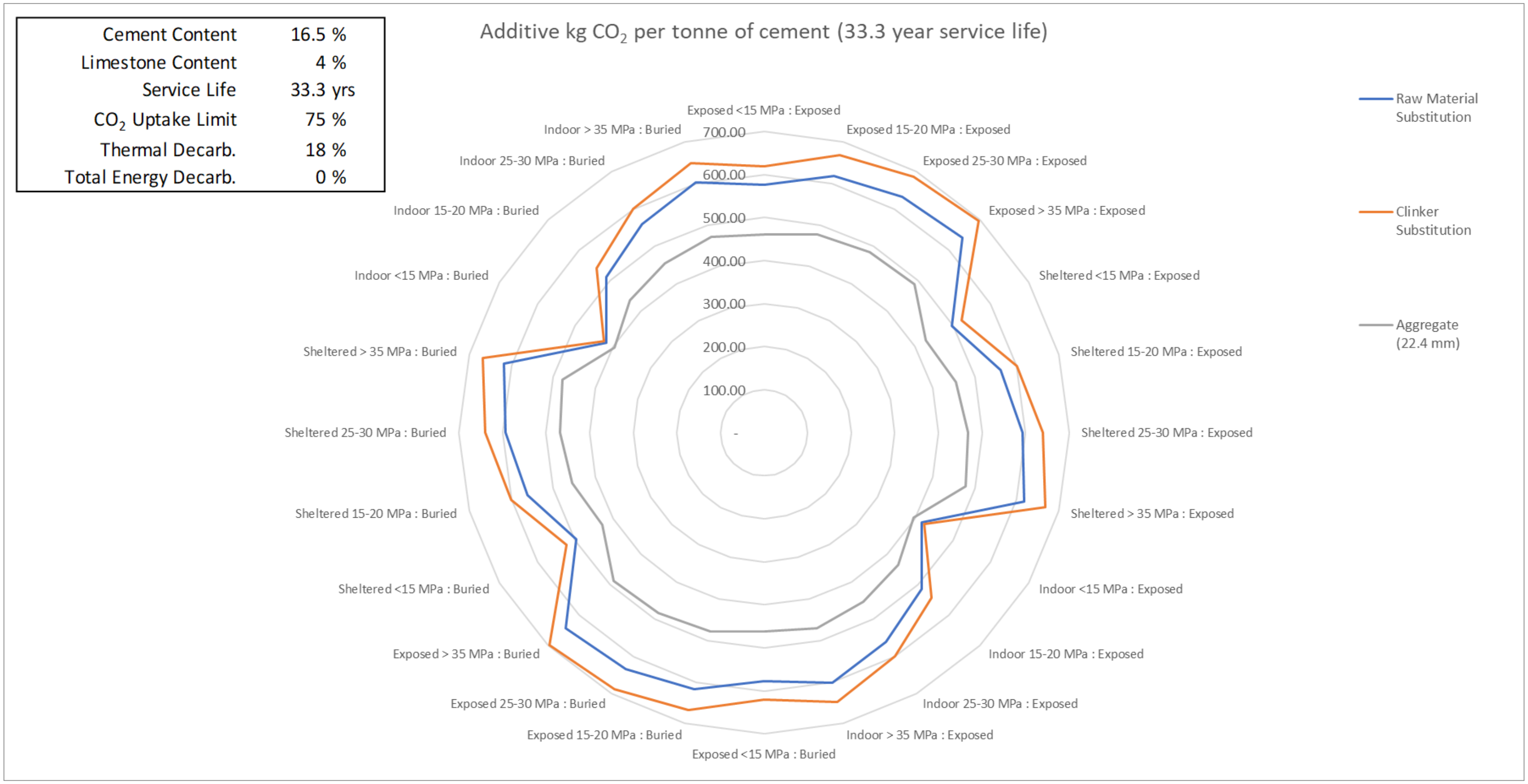


*Figure 7.20: Thermal Energy Decarbonization – 33.3 year service life*

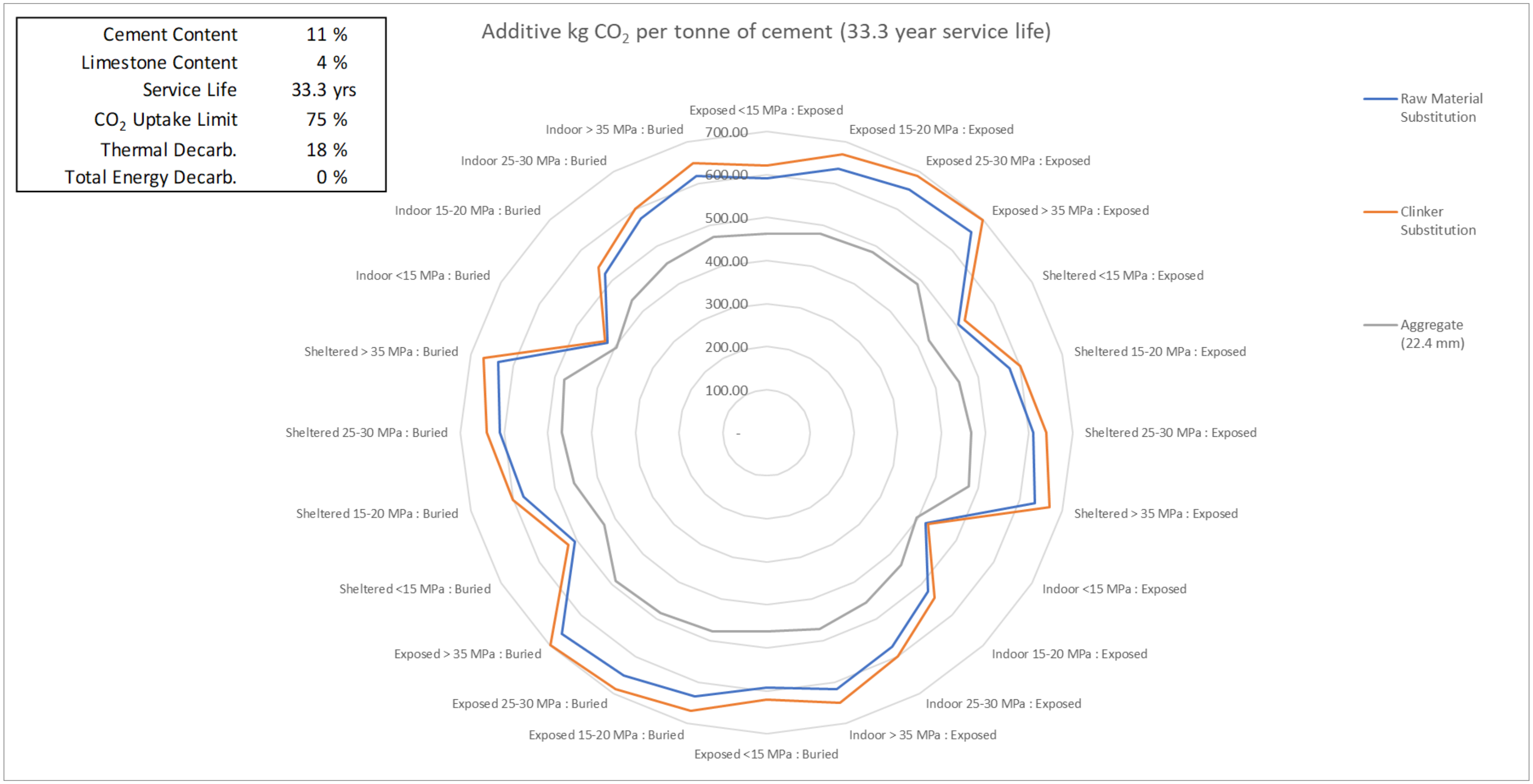


*Figure 7.21: Thermal Energy Decarbonization – 33.3 year service life*

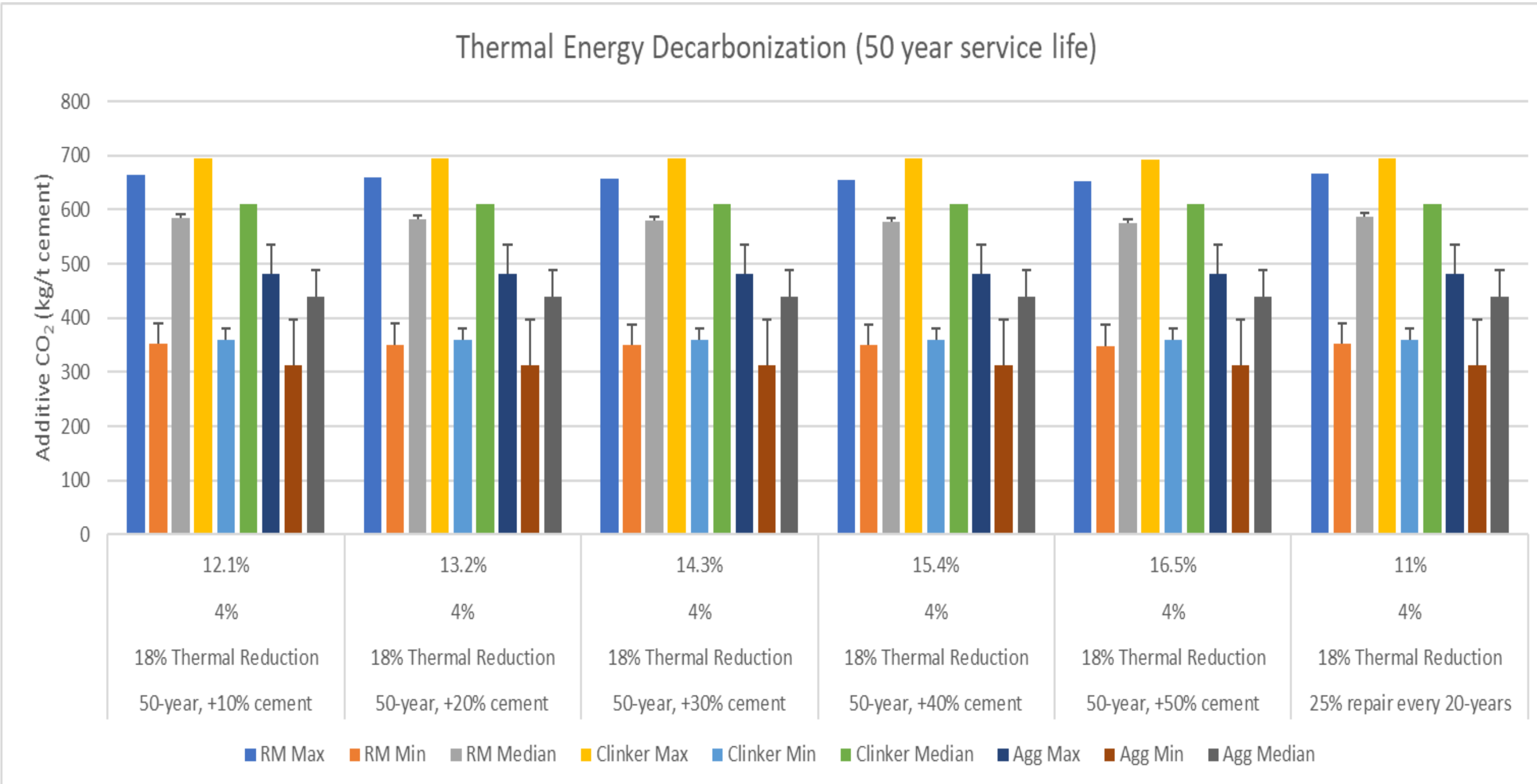


*Figure 7.22: Thermal Energy Decarbonization – 50 year service life*

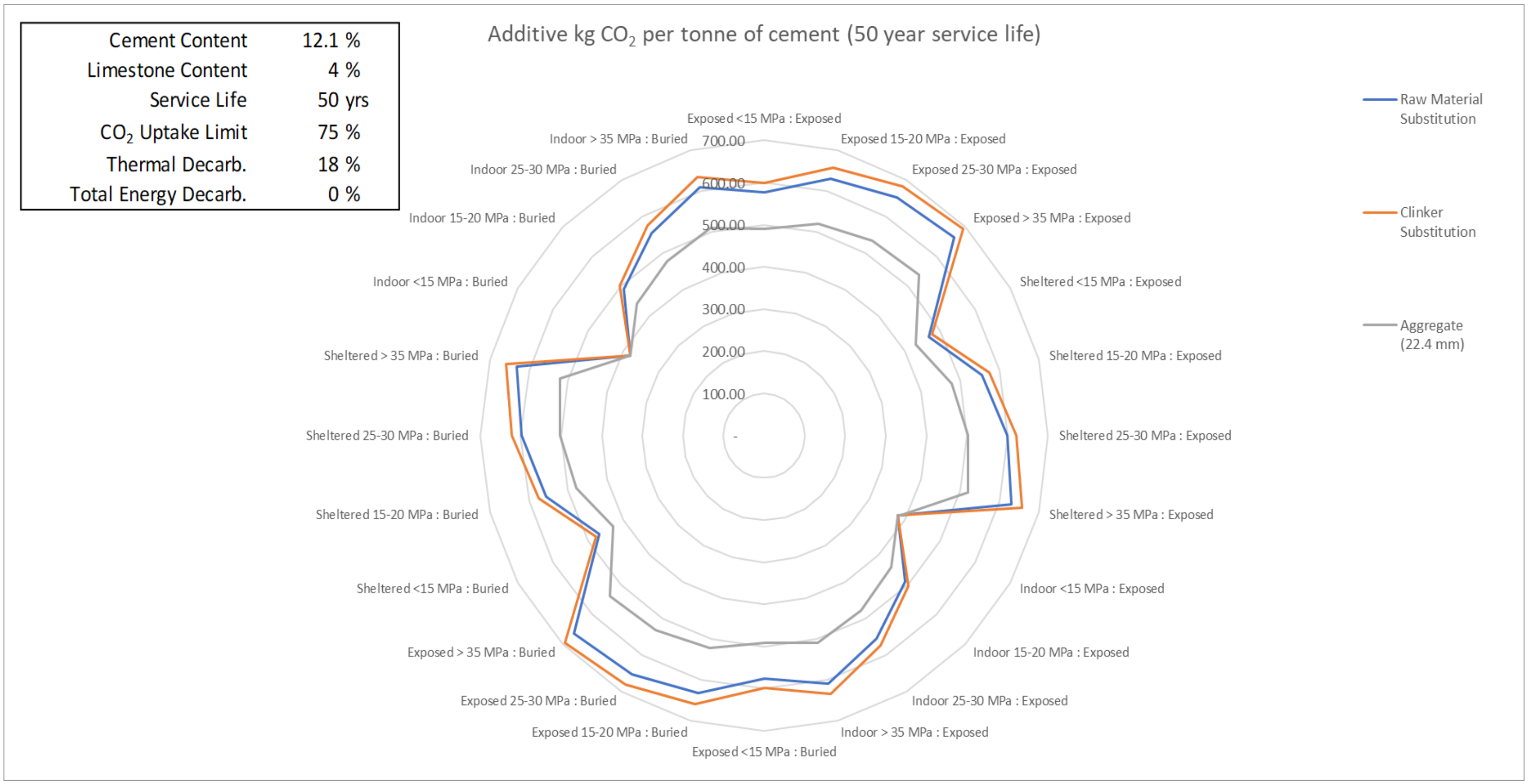


*Figure 7.23: Thermal Energy Decarbonization – 50 year service life*

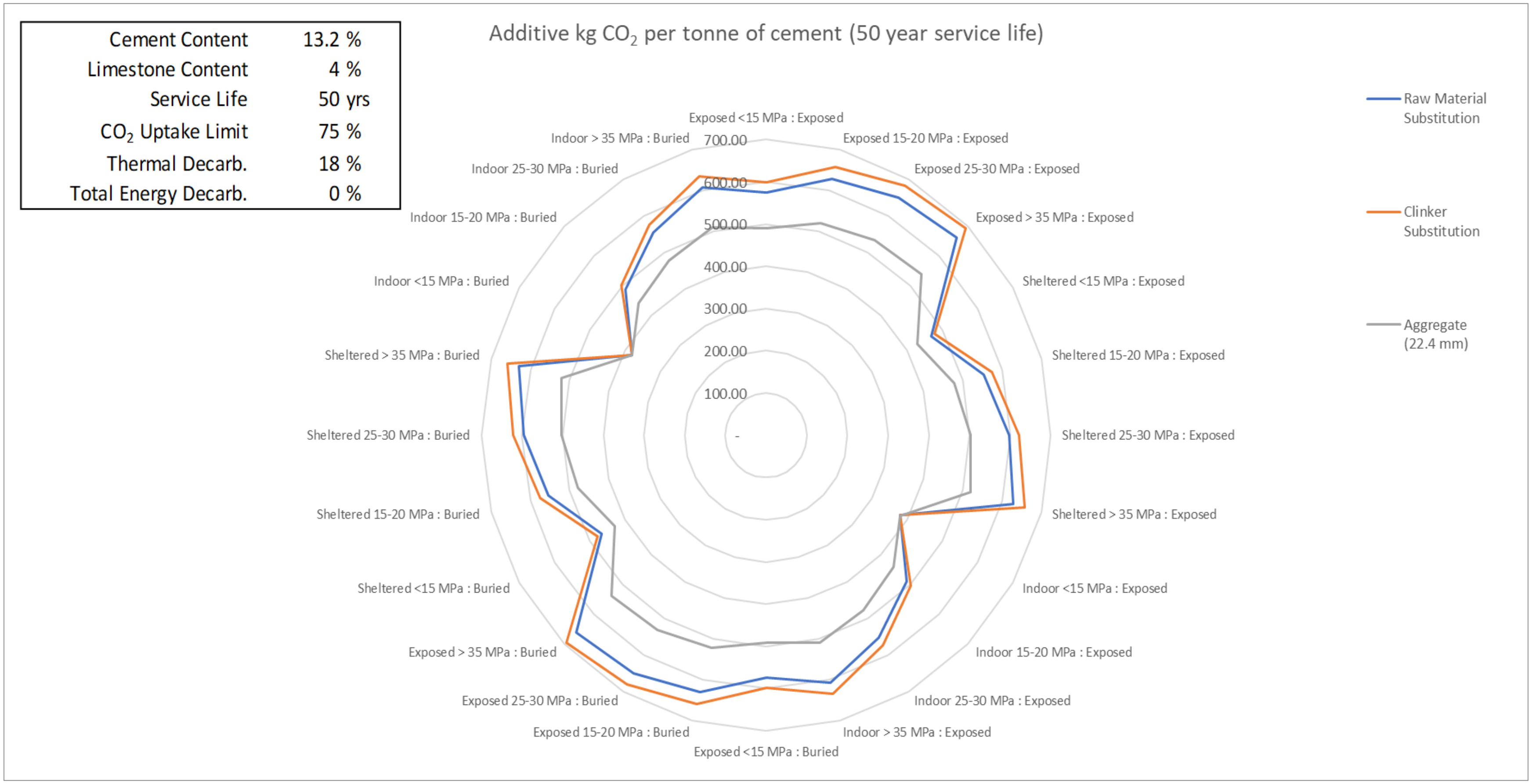


*Figure 7.24: Thermal Energy Decarbonization – 50 year service life*

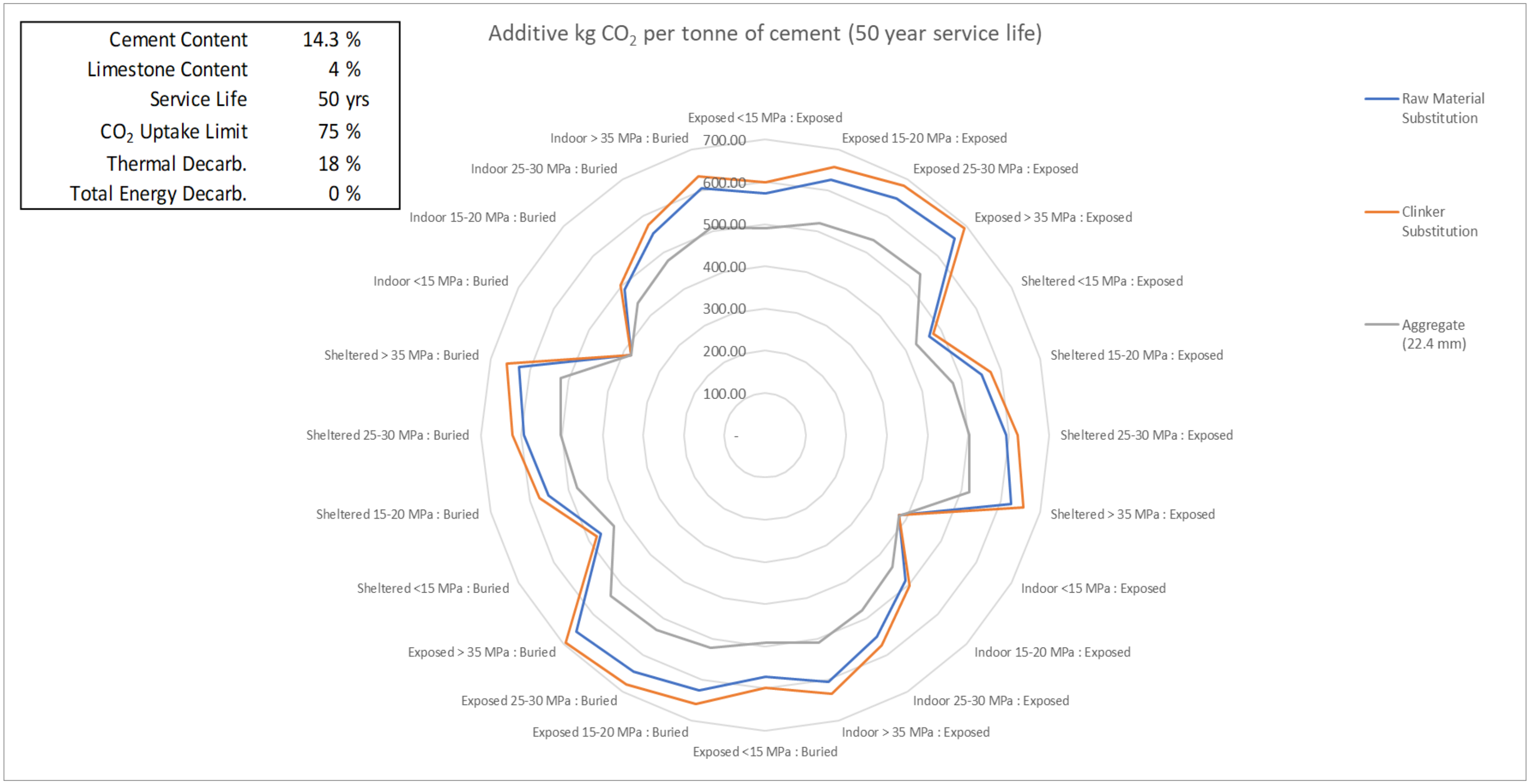


*Figure 7.25: Thermal Energy Decarbonization – 50 year service life*

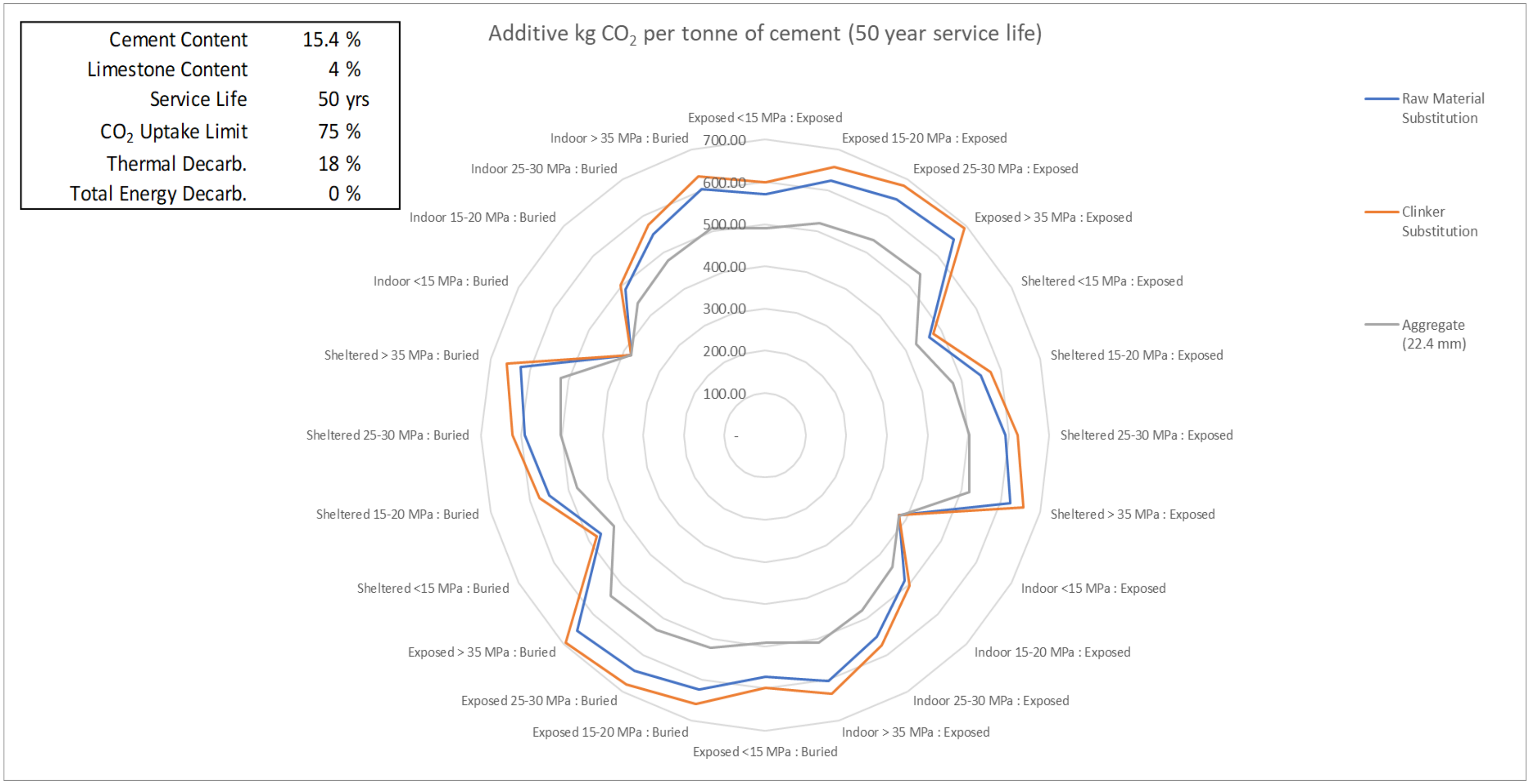


*Figure 7.26: Thermal Energy Decarbonization – 50 year service life*

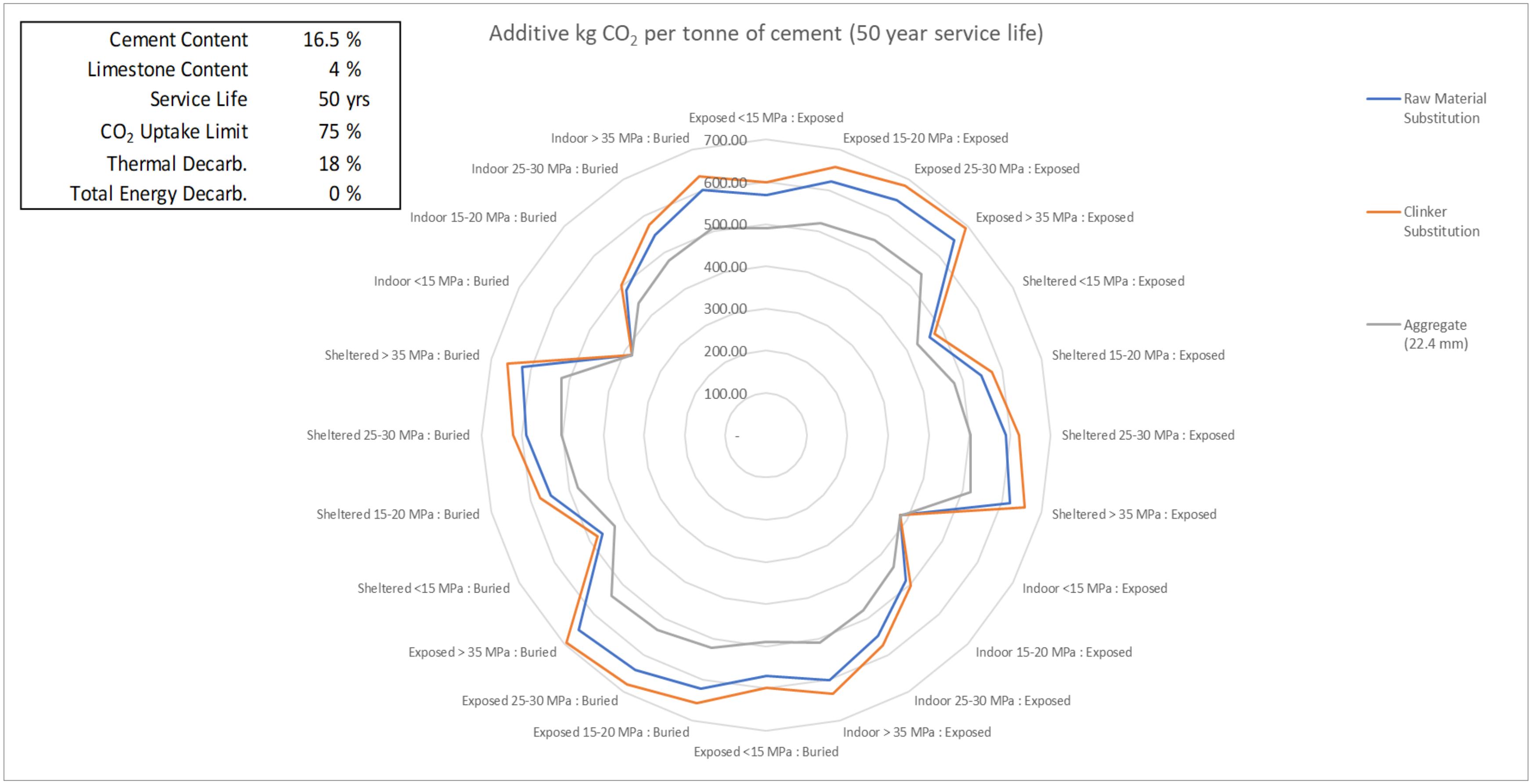


*Figure 7.27: Thermal Energy Decarbonization – 50 year service life*

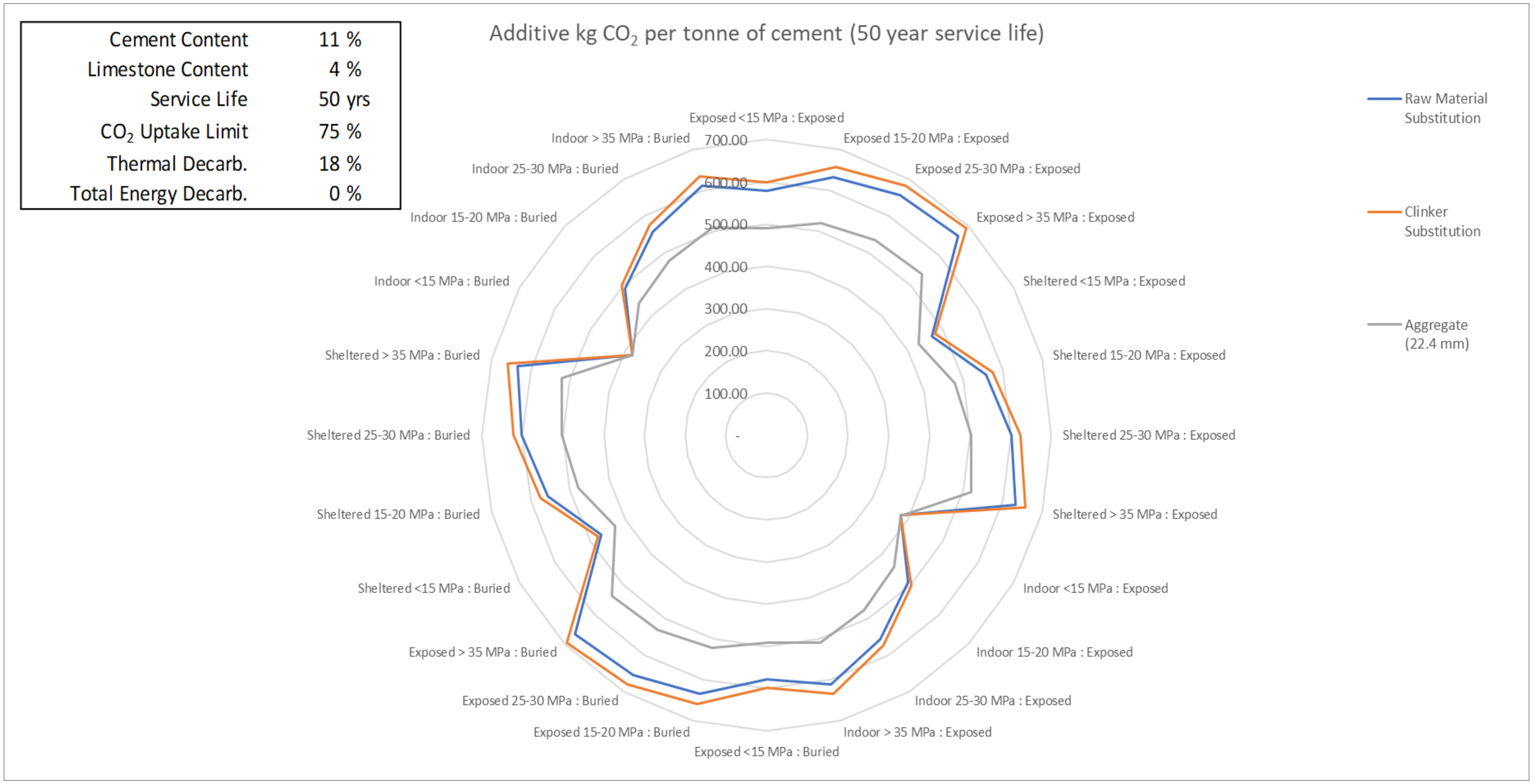


*Figure 7.28: Thermal Energy Decarbonization – 50 year service life*

### 7.5.1 Results and Interpretation of Thermal Energy Decarbonization (18%)

The Thermal Energy Decarbonization (18%) scenarios result in further reductions of the additive $CO_2$/t cement from the Life Extension scenarios. Carbon dioxide uptake has a significant benefit as clearly visible in all of the radar graphs which is apparent in indoor use concrete that is less than 15 MPa which has the fastest carbon dioxide uptake rate. As expected, longer service life leads to similar results regardless of secondary use as maximum carbon dioxide uptake is reached. Secondary use as aggregates results in the lowest additive $CO_2$/t cement emissions as expected for all scenarios due to the continued $CO_2$ uptake by aggregates during the secondary use.

Thermal energy decarbonization further reduces the additive emissions and, in combination with life extension, is a valid approach for the Canadian cement industry to reduce additive $CO_2$ emissions.

## 7.6 Limestone Addition

Figures 7.29 and 7.36 show the results of maximum, minimum and median additive carbon dioxide emissions associated with avoidance through limestone addition of 15% (Canadian regulatory limit). The results also highlight the potential error for each scenario as mentioned in Section 7.3 and are illustrated with the error bars in the graphs. The additive carbon dioxide emissions for each type of application and concrete strength as detailed in Section 7.2 are presented in Figures 7.30 through 7.35 and Figures 7.37 through 7.42 for a 33.3 and 50-year service life, respectively.

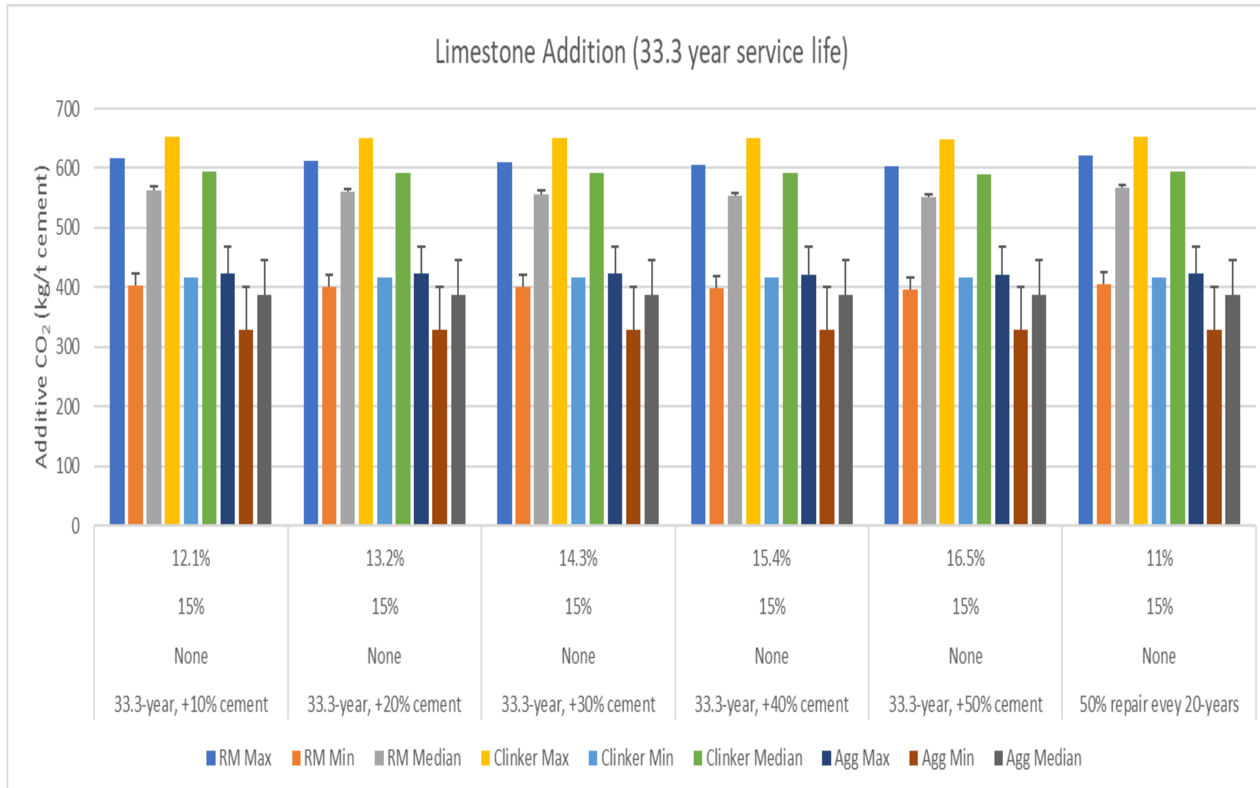


*Figure 7.29: Limestone Addition – 33.3 year service life*

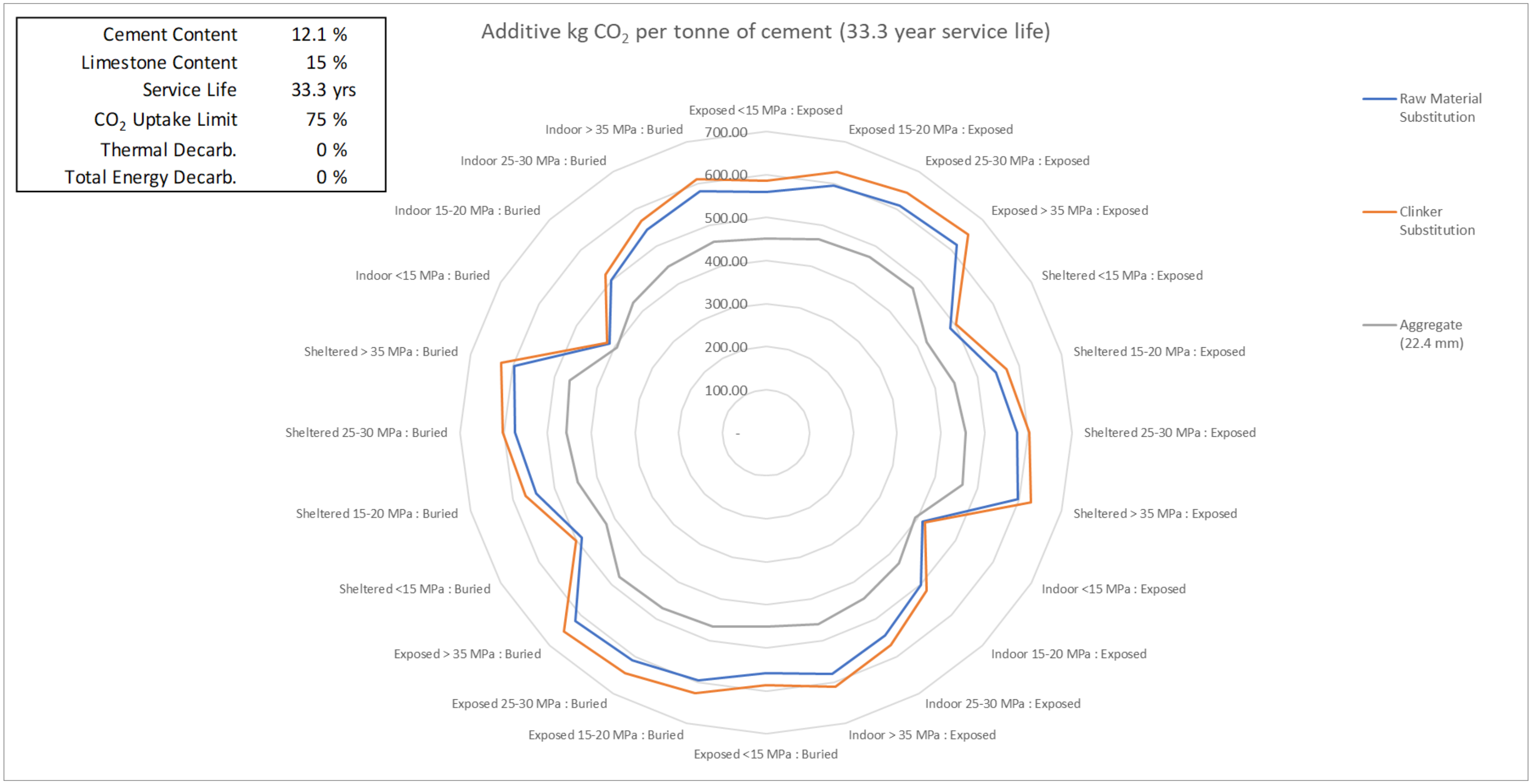


*Figure 7.30: Limestone Addition – 33.3 year service life*

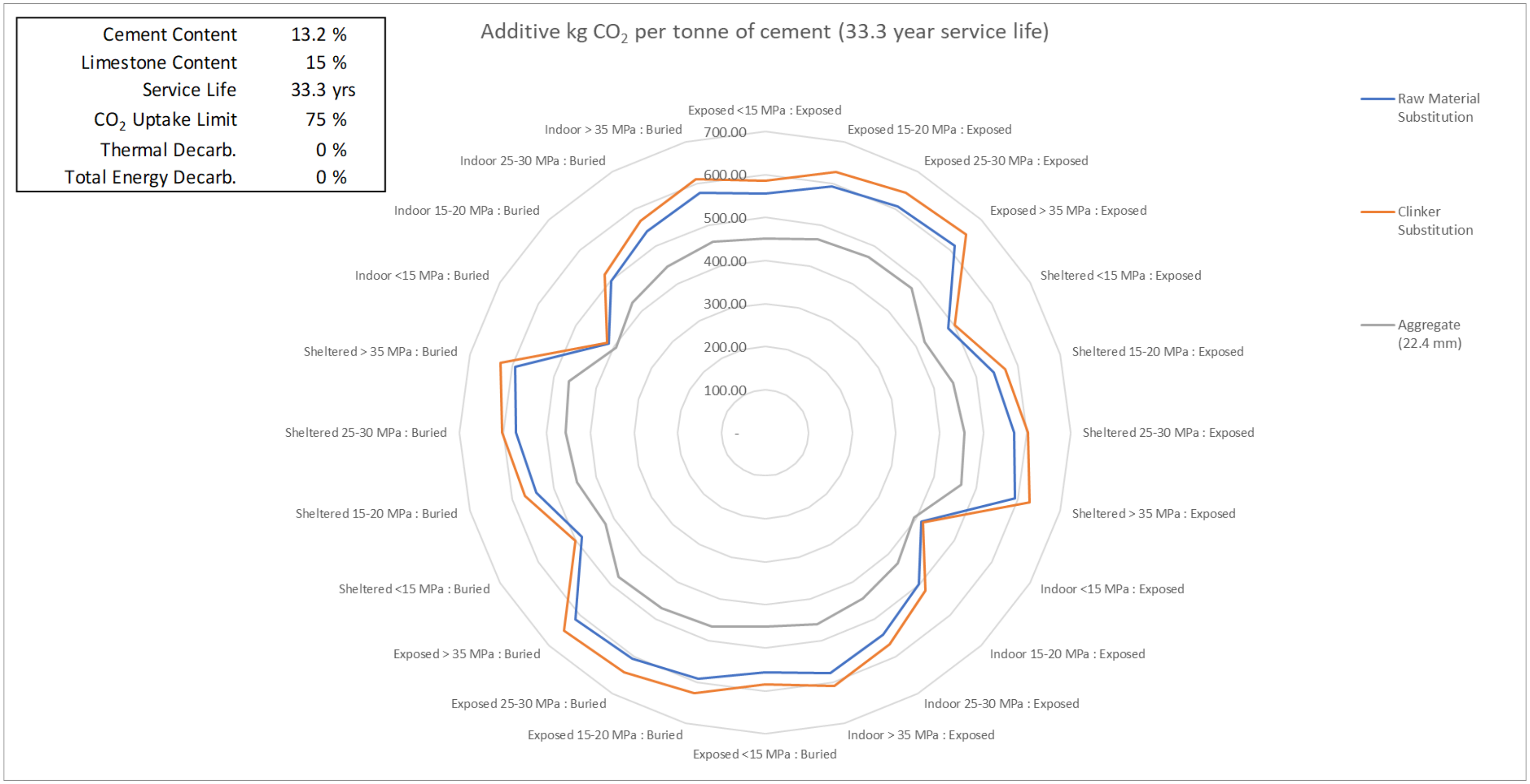


*Figure 7.31: Limestone Addition – 33.3 year service life*

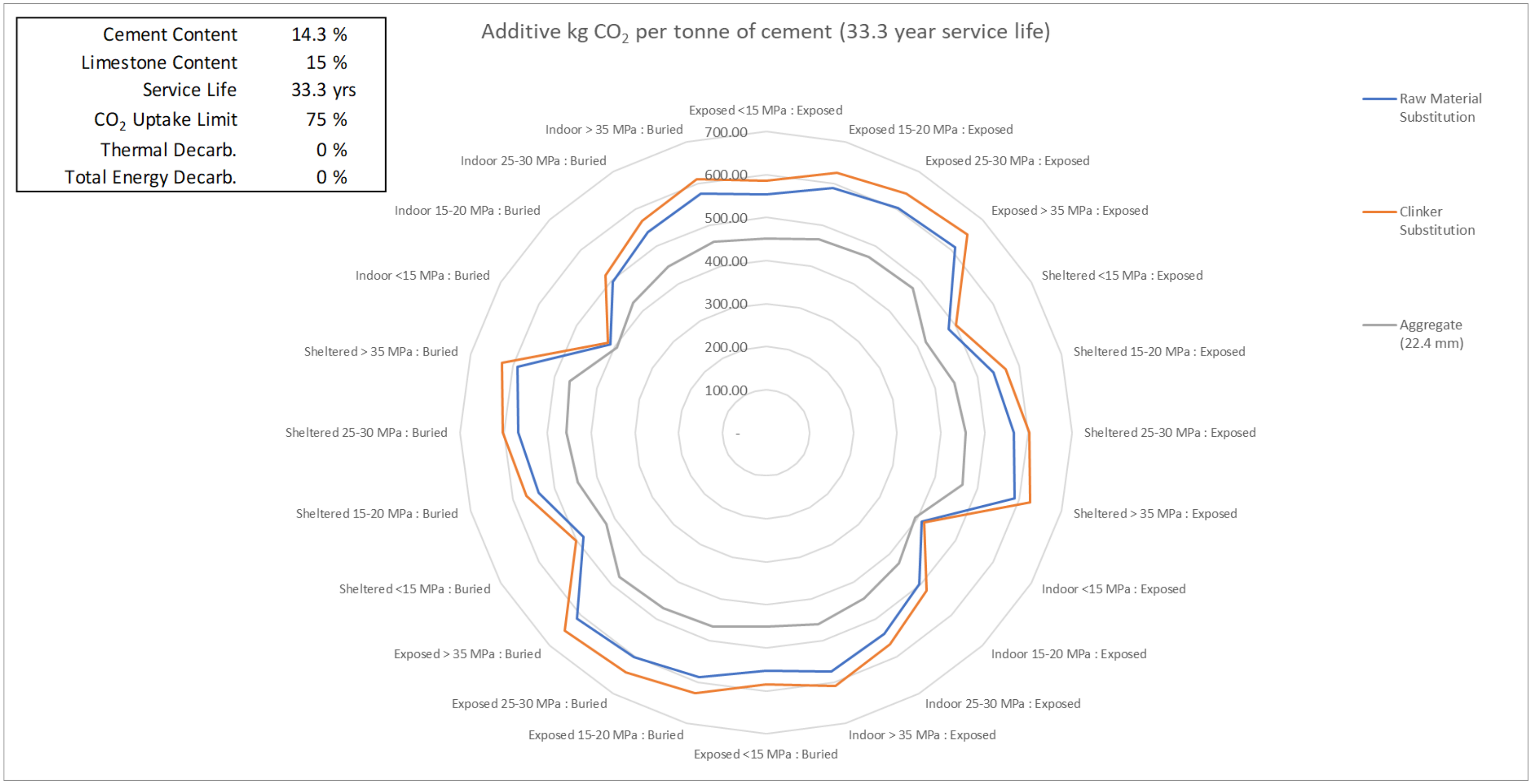


*Figure 7.32: Limestone Addition – 33.3 year service life*

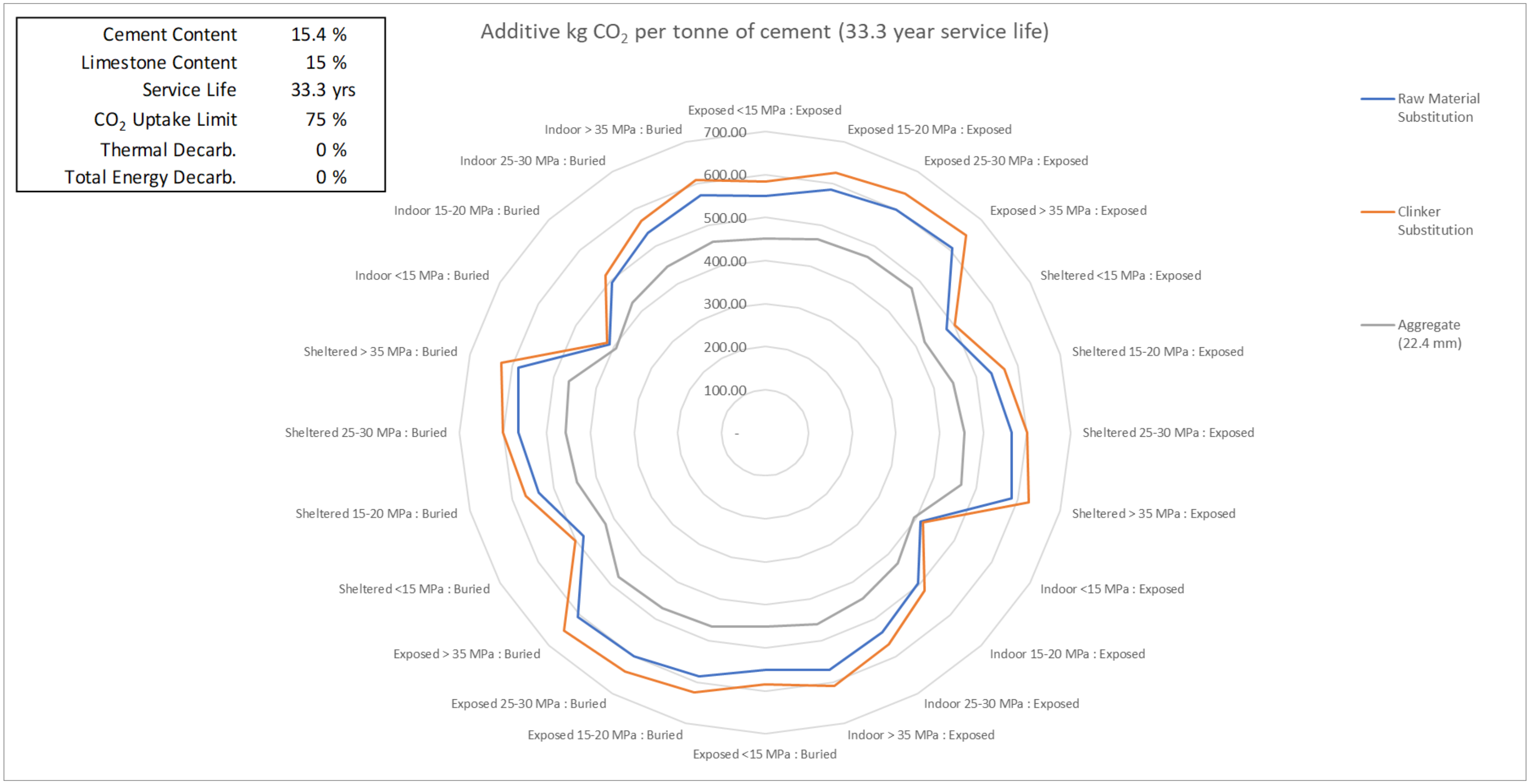


*Figure 7.33: Limestone Addition – 33.3 year service life*

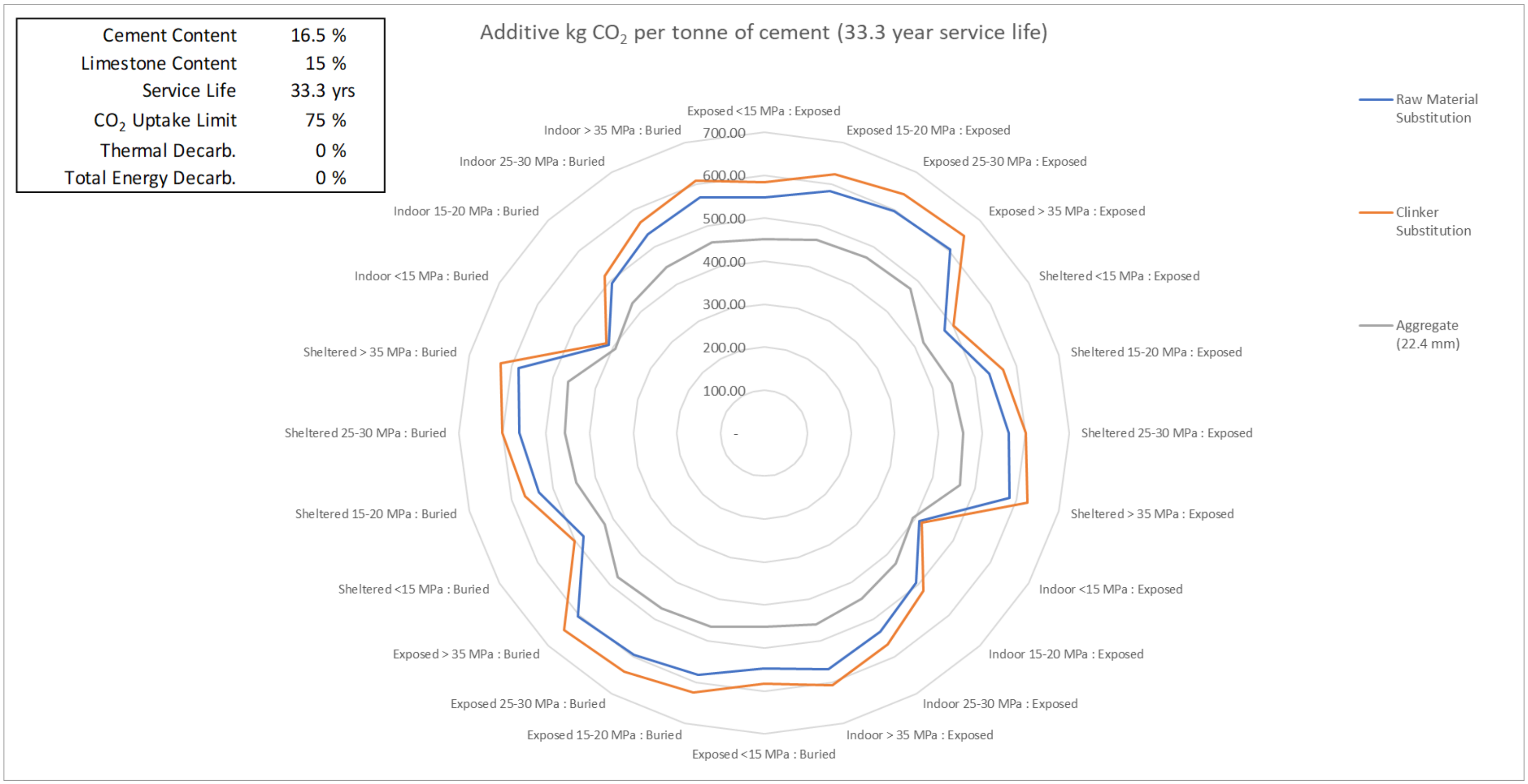


*Figure 7.34: Limestone Addition – 33.3 year service life*

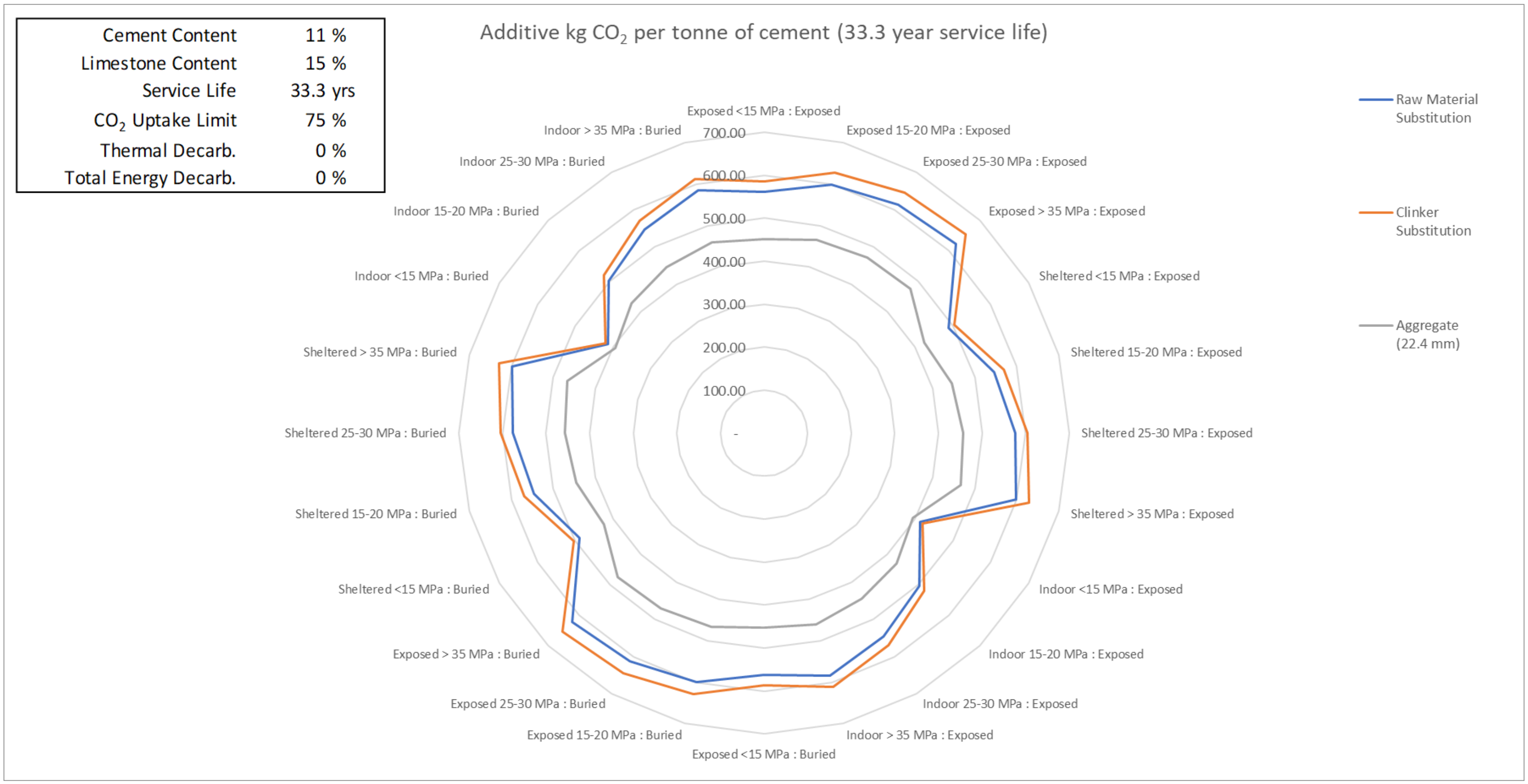


*Figure 7.35: Limestone Addition – 33.3 year service life*

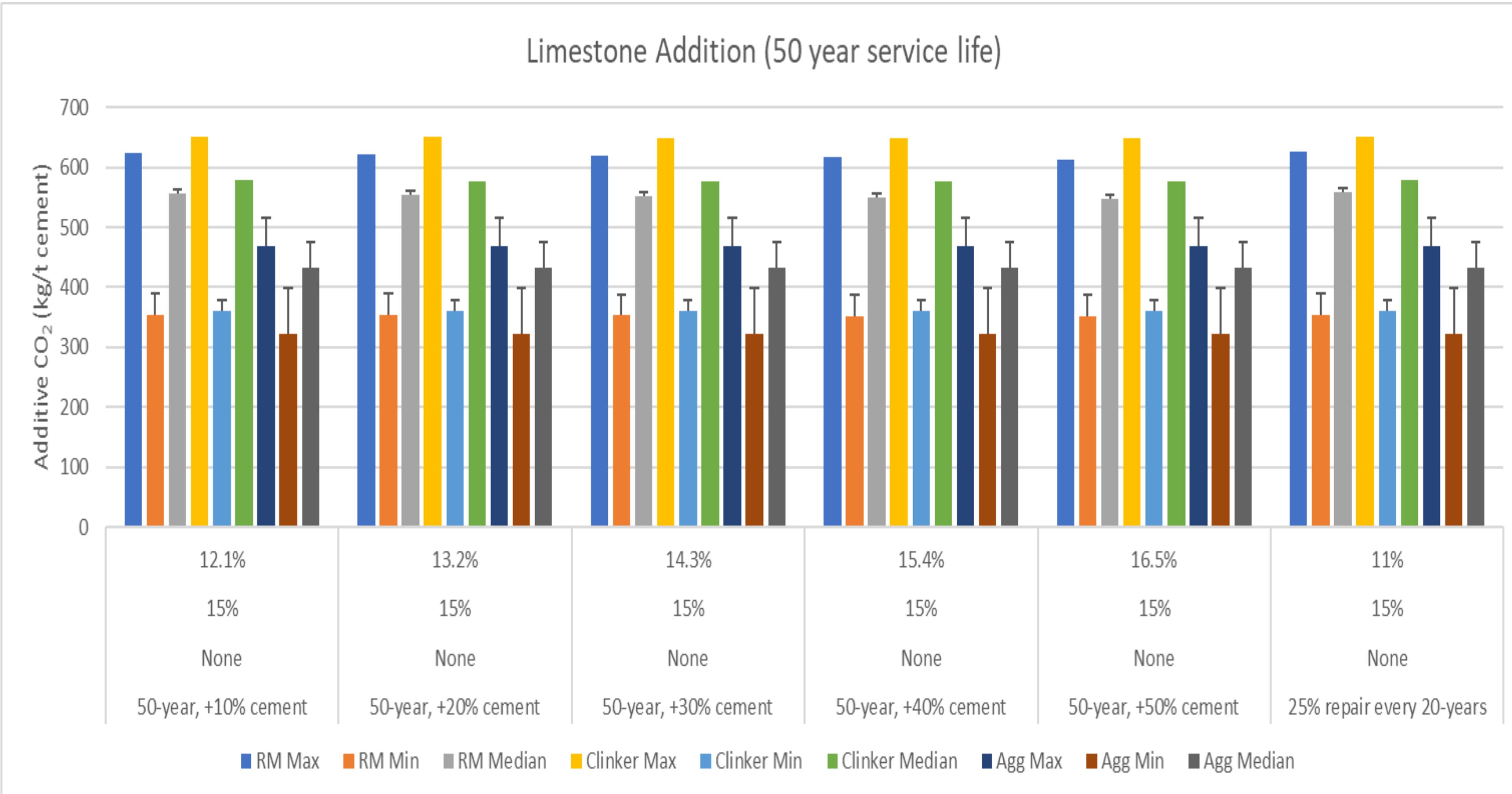


*Figure 7.36: Limestone Addition – 50 year service life*

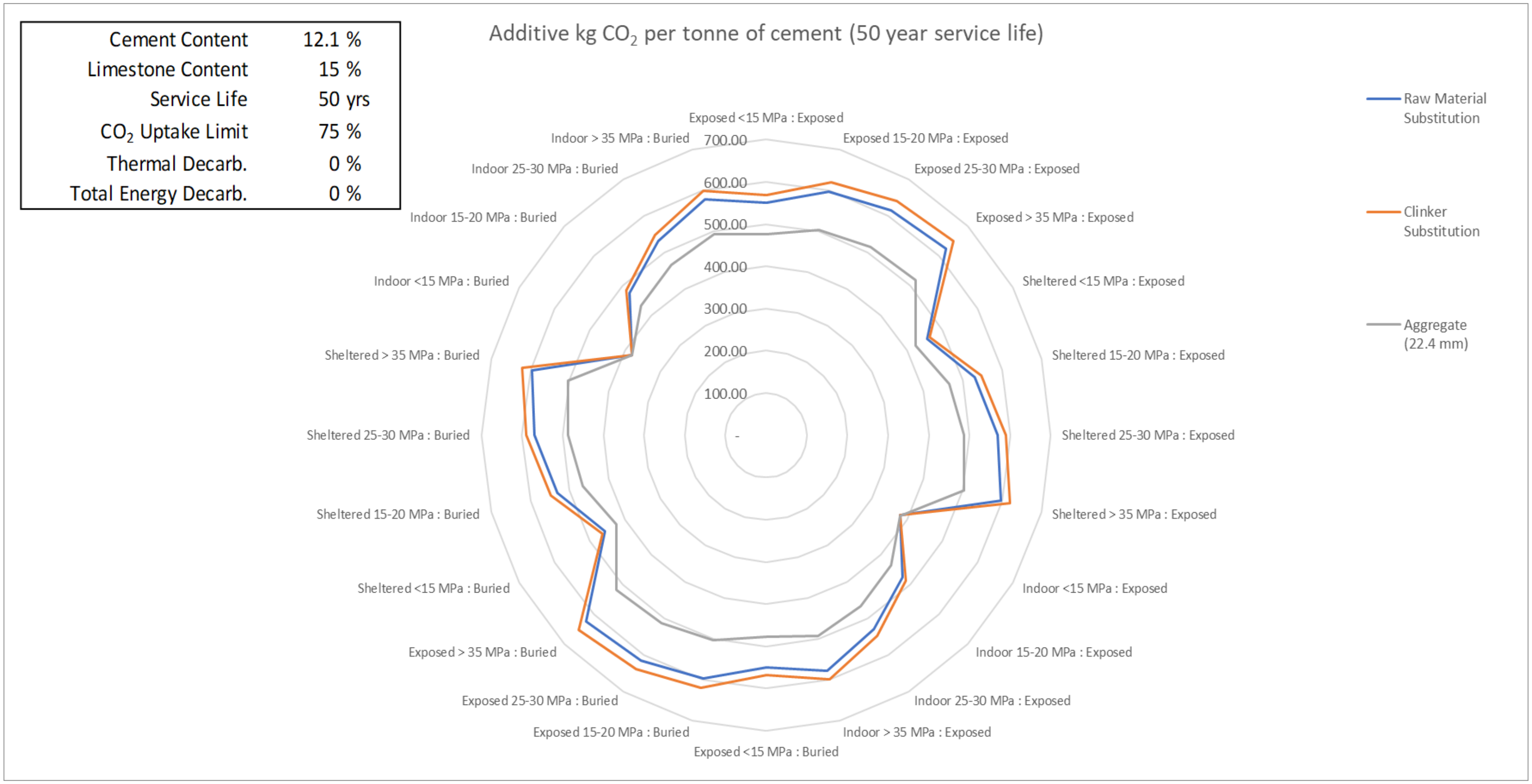


*Figure 7.37: Limestone Addition – 50 year service life*

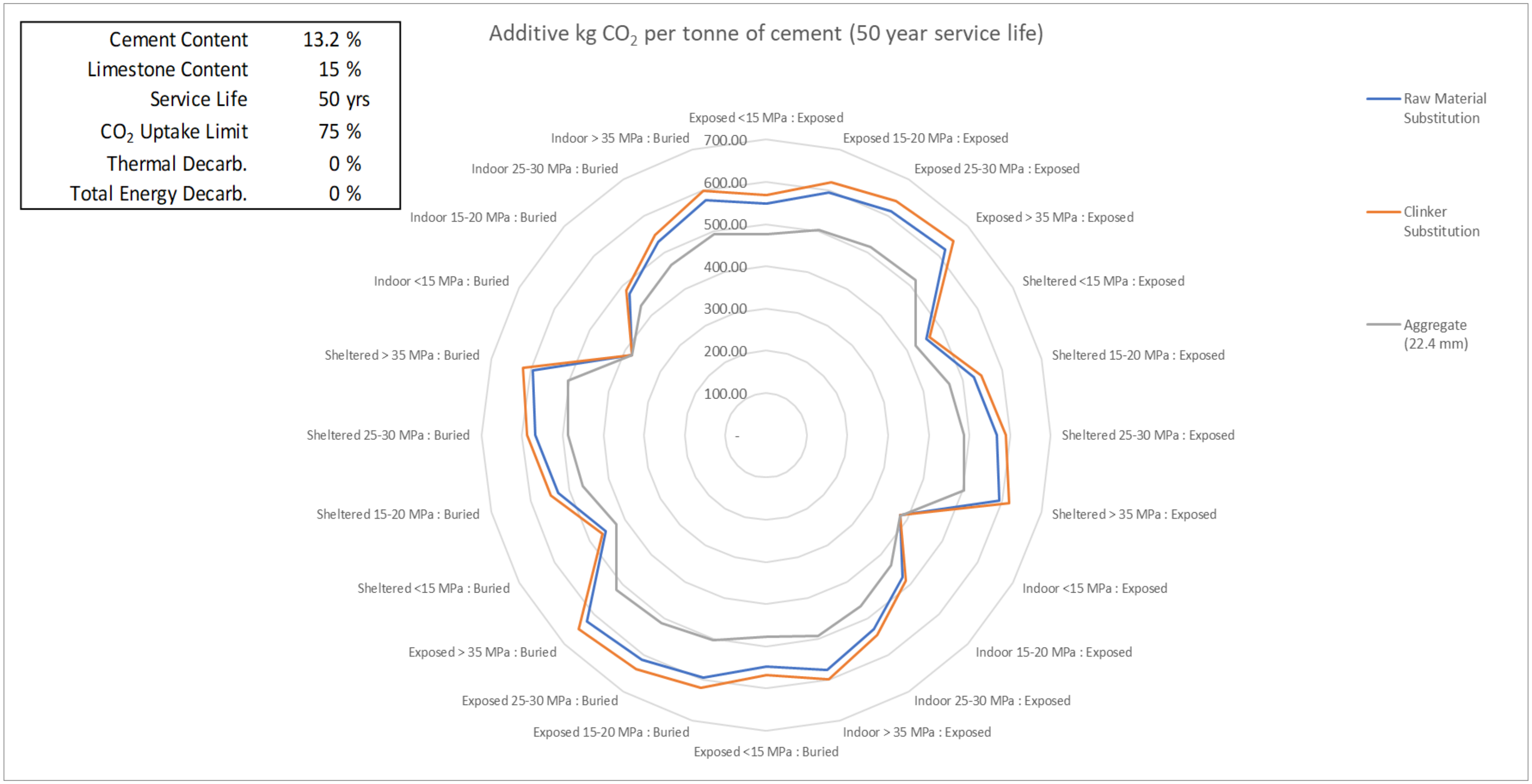


*Figure 7.38: Limestone Addition – 50 year service life*

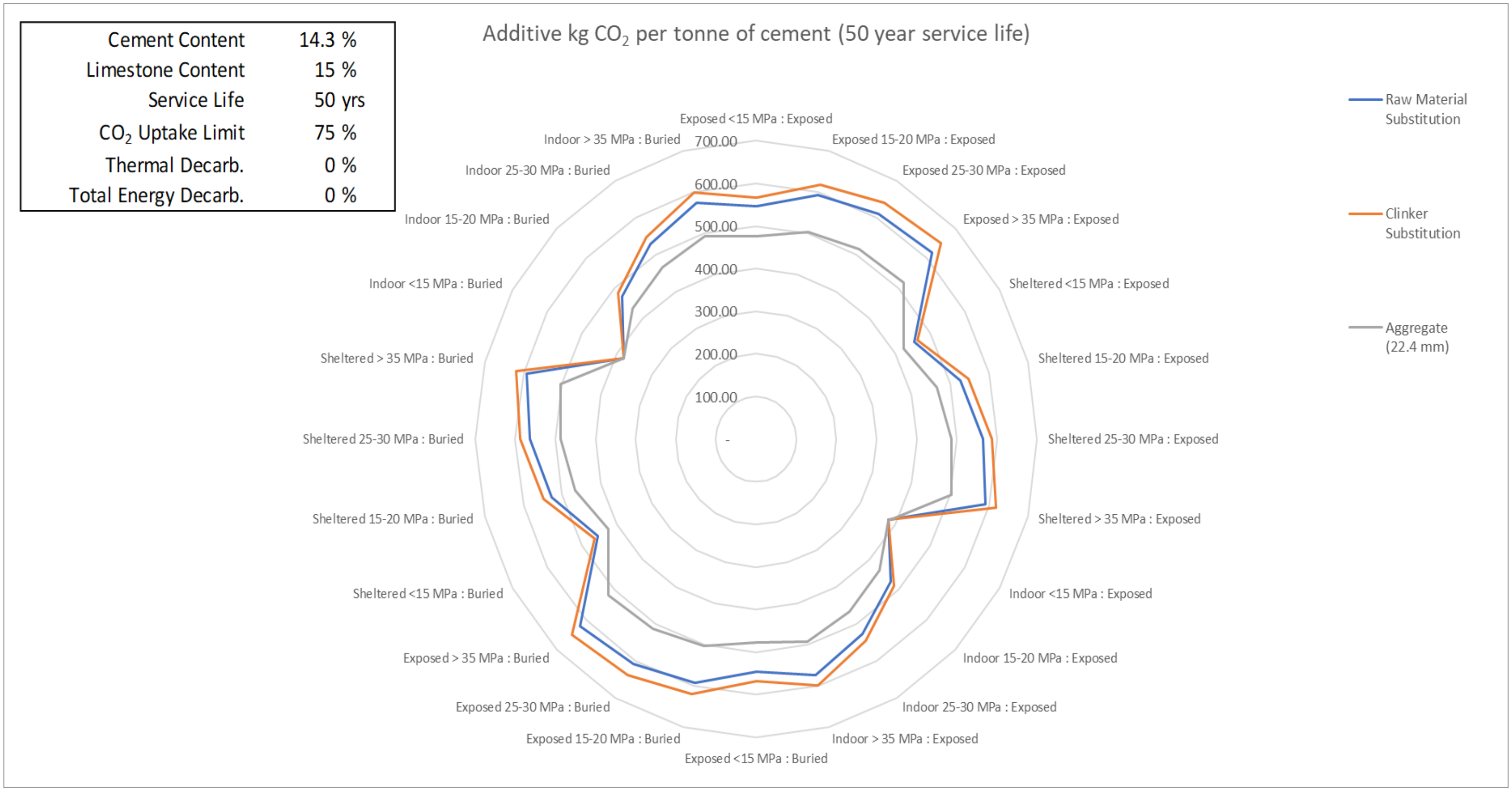


*Figure 7.39: Limestone Addition – 50 year service life*

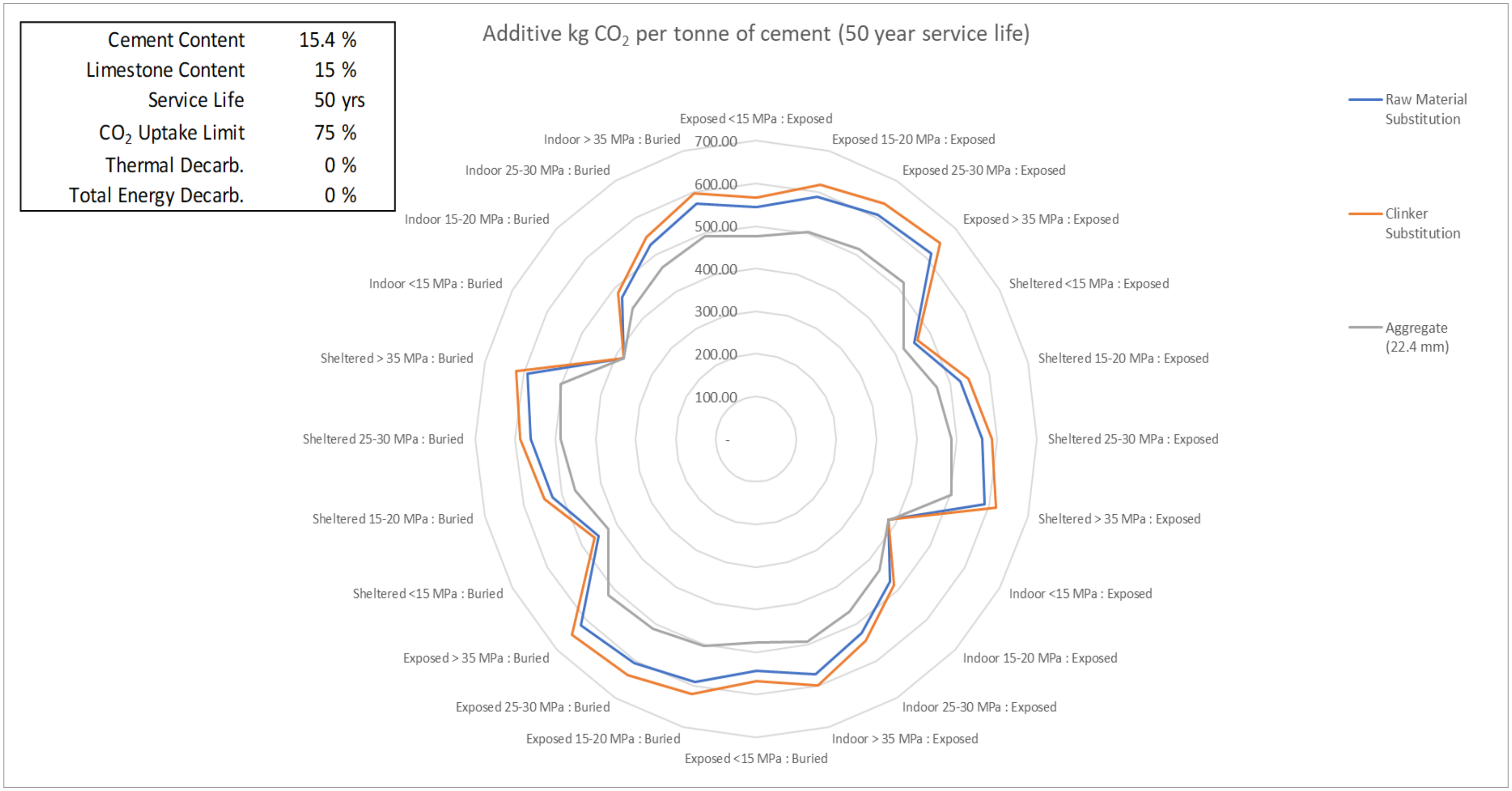


*Figure 7.40: Limestone Addition – 50 year service life*

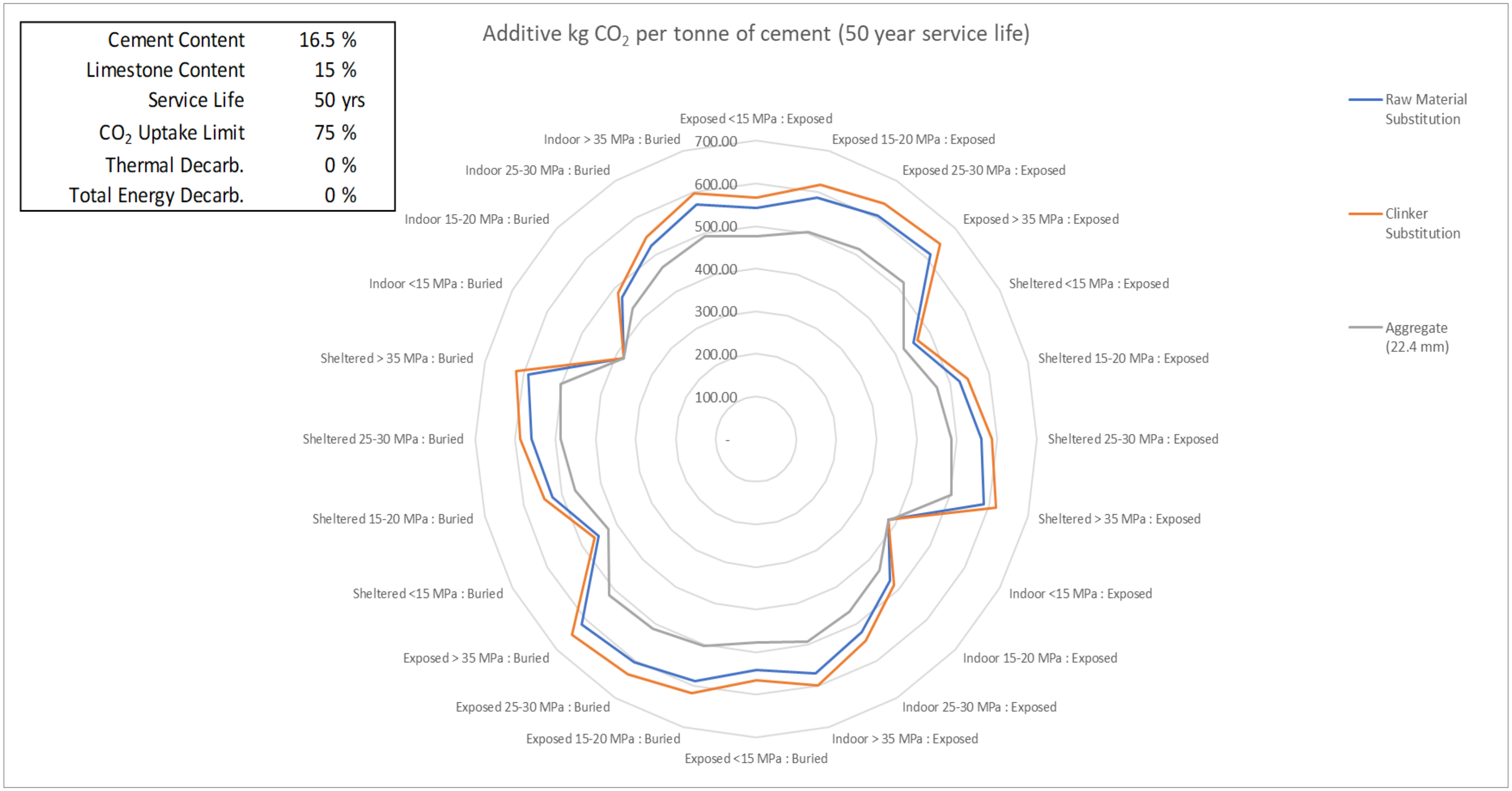


*Figure 7.41: Limestone Addition – 50 year service life*

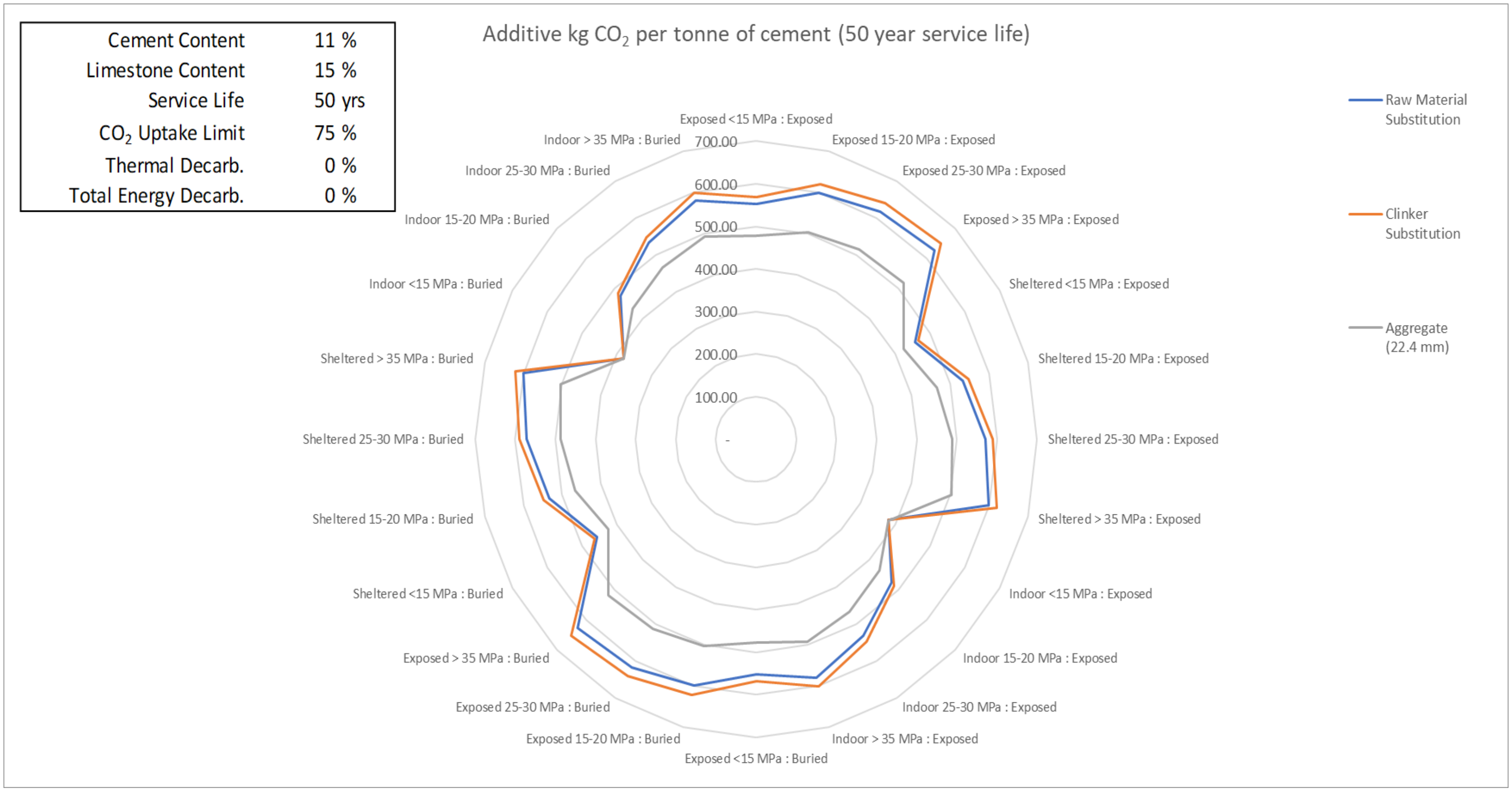


*Figure 7.42: Limestone Addition – 50 year service life*

### 7.6.1 Results and Interpretation of Limestone Addition (15%)

The Limestone Addition (15%) scenarios result in a greater impact than Thermal Decarbonization in reducing the additive $CO_2$/t cement. This is expected as limestone addition reduces both thermal emissions as well as calcination emissions. Secondary use as aggregate results in the lowest additive $CO_2$/t cement emissions as expected for all scenarios due to the continued $CO_2$ uptake by the aggregates during the secondary use. However, the raw material and clinker substitution gap to aggregate use is smaller in the limestone addition scenario due to the lower available CaO. It is clear from these scenarios that available CaO (ie. ability to uptake carbon dioxide) has the greatest impact on additive emissions associated with aggregate use.

Limestone addition is clearly a benefit to lower additive $CO_2$ emissions in the Canadian cement industry and an opportunity simply by reaching existing legislative limits of 15% (Cement Association of Canada, 2020).

Of course, thermal decarbonization and limestone addition are not mutually exclusive – as such, Section 7.7 evaluates the benefit of combining the two actions.

## 7.7 Limestone Addition + Thermal Decarbonization

Figures 7.43 and 7.50 show the results of maximum, minimum and median additive carbon dioxide emissions associated with avoidance through limestone addition at 15% (Canadian regulatory limit) and thermal energy decarbonization based on a reduction equivalent to reaching the levels of the Germany cement industry. The results also highlight the potential error for each scenario as mentioned in Section 7.3 and are illustrated with the error bars in the graphs. The additive carbon dioxide emissions for each type of application and concrete strength as detailed in Section 7.2 are presented in Figures 7.44 through 7.49 and Figures 7.51 through 7.56 for a 33.3 and 50-year service life, respectively.

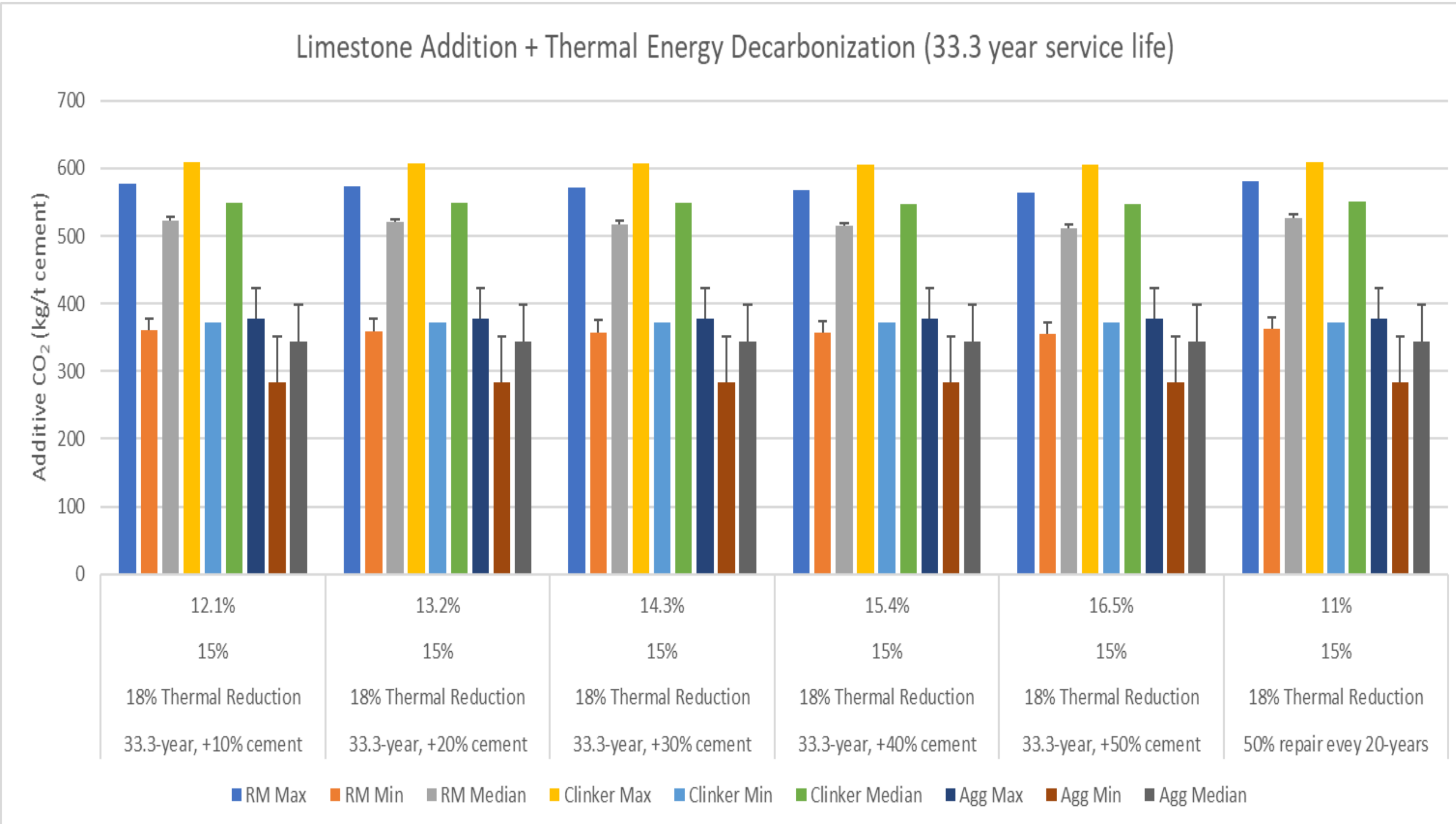


*Figure 7.43: Limestone Addition & Thermal Energy Decarbonization – 33.3 year service life*

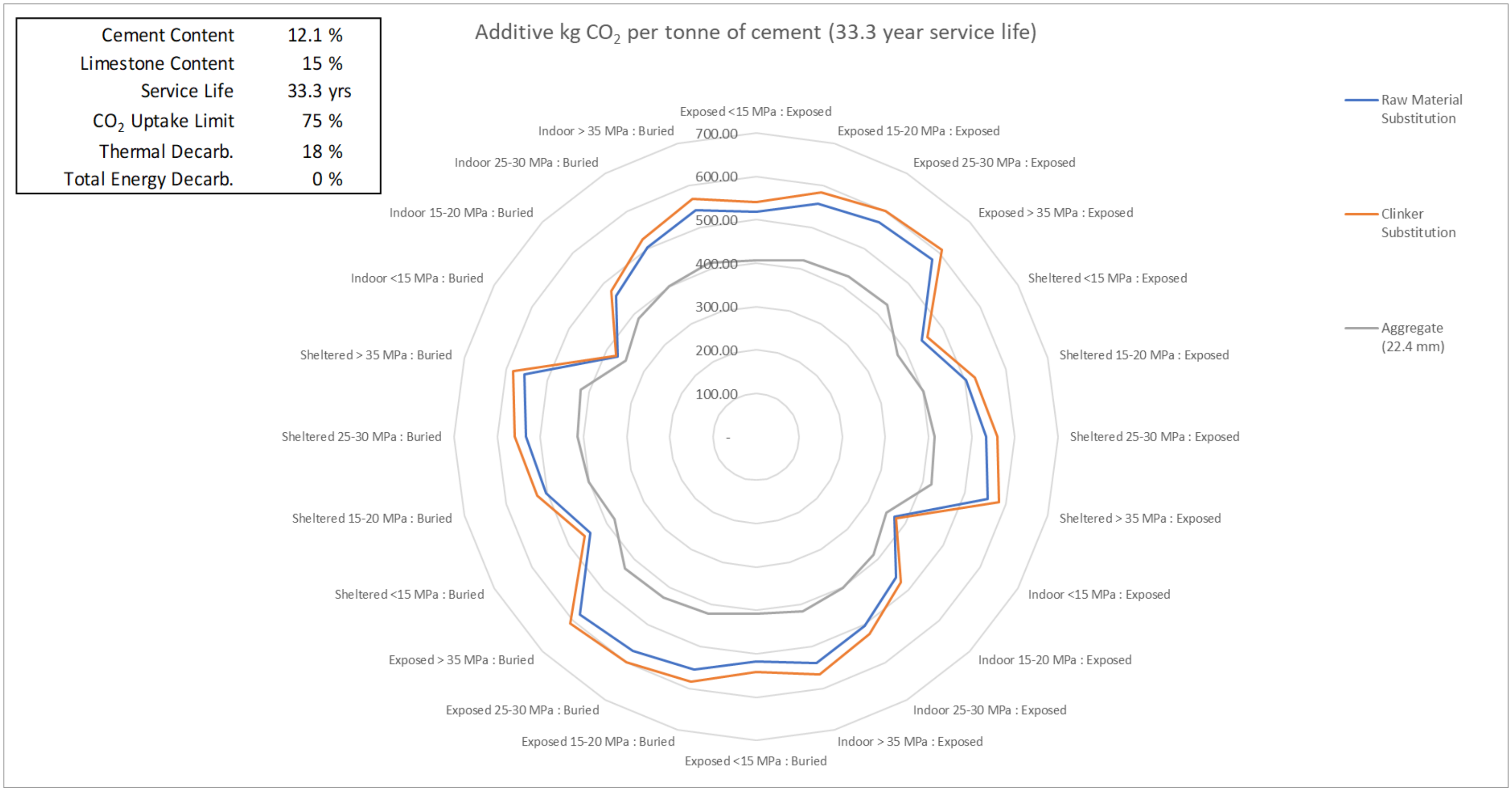


*Figure 7.44: Limestone Addition & Thermal Energy Decarbonization – 33.3 year service life*

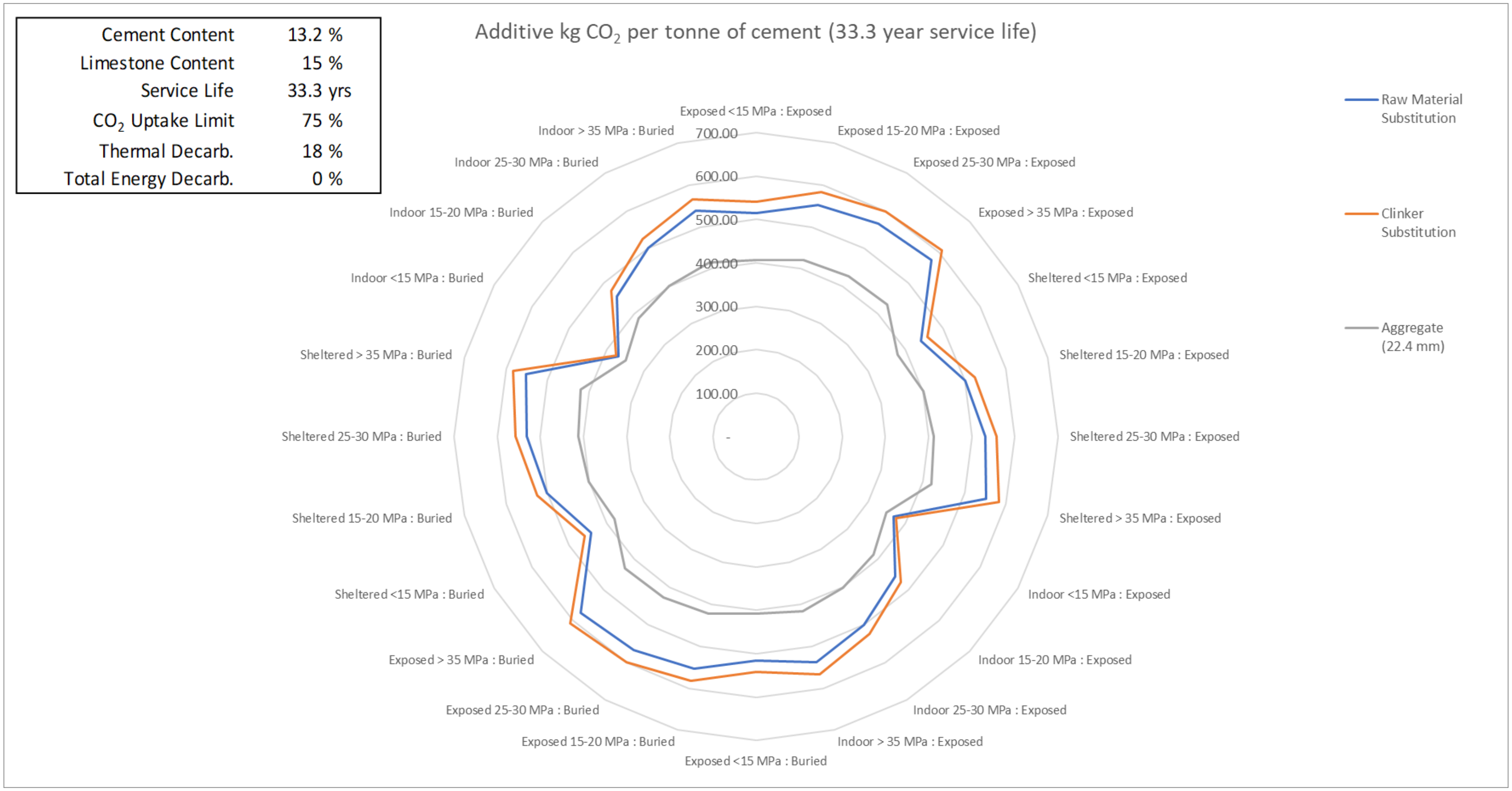


*Figure 7.45: Limestone Addition & Thermal Energy Decarbonization – 33.3 year service life*

| | |
|---|---|
| Cement Content | 14.3 % |
| Limestone Content | 15 % |
| Service Life | 33.3 yrs |
| $CO_2$ Uptake Limit | 75 % |
| Thermal Decarb. | 18 % |
| Total Energy Decarb. | 0 % |

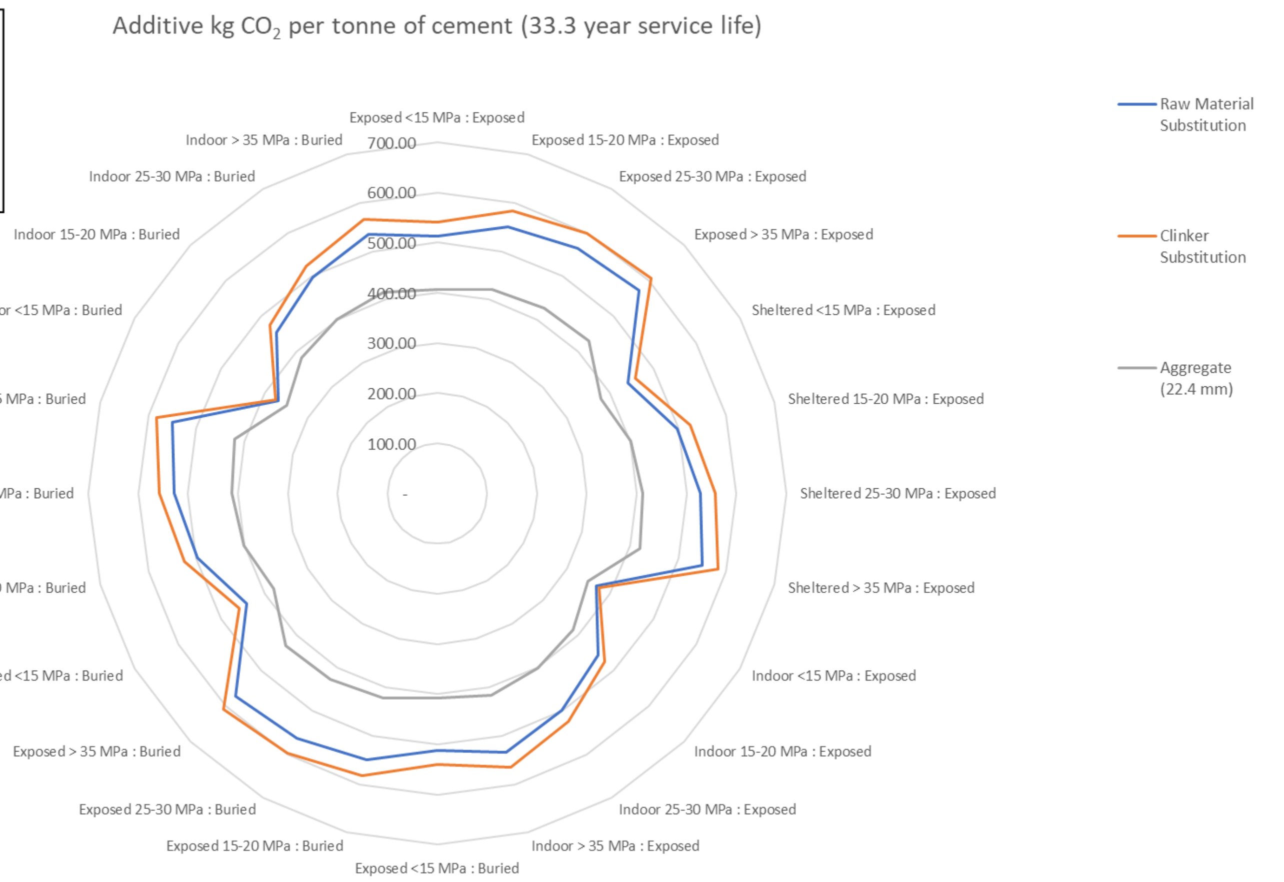


*Figure 7.46: Limestone Addition & Thermal Energy Decarbonization – 33.3 year service life*

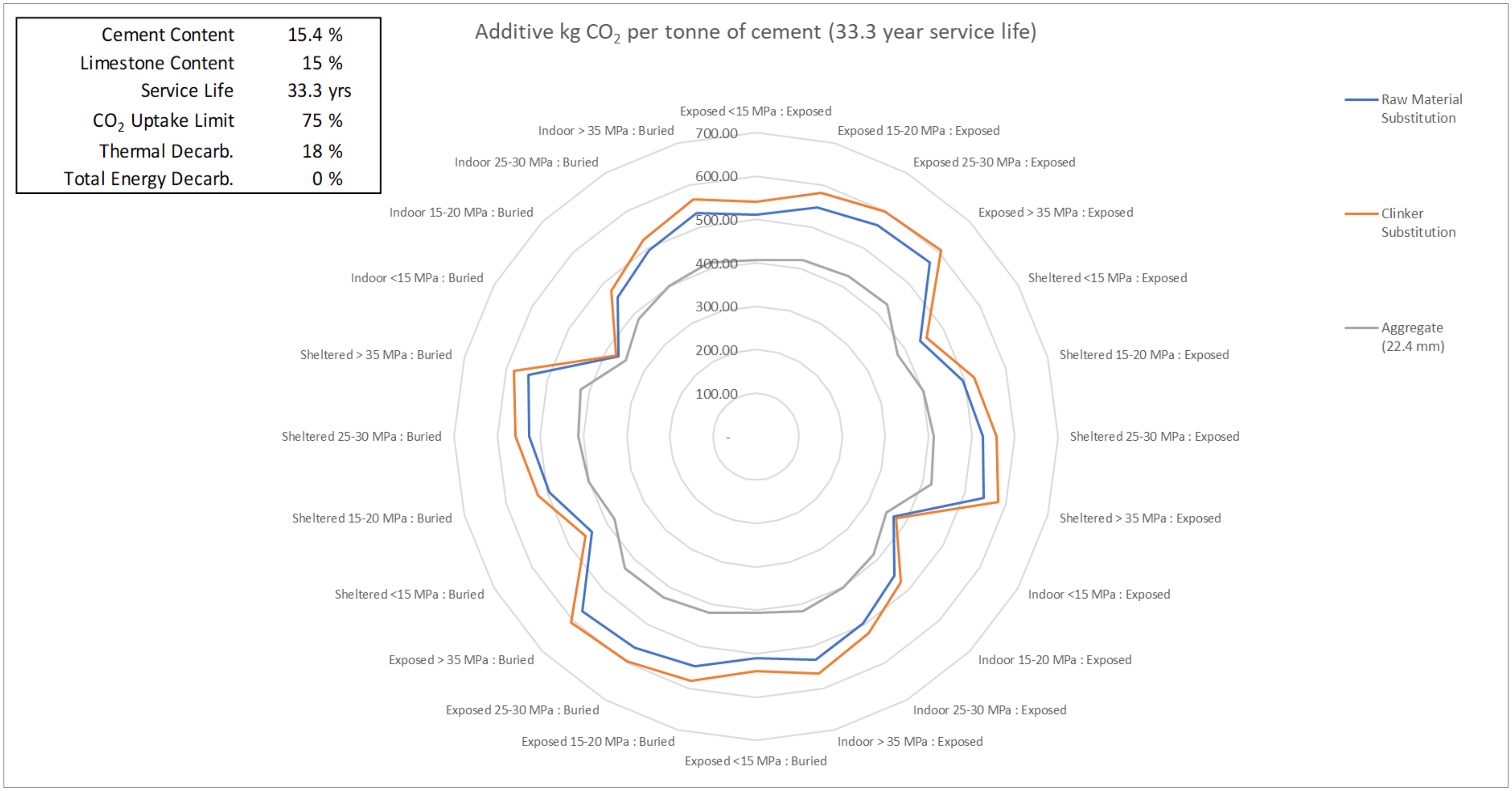


*Figure 7.47: Limestone Addition & Thermal Energy Decarbonization – 33.3 year service life*

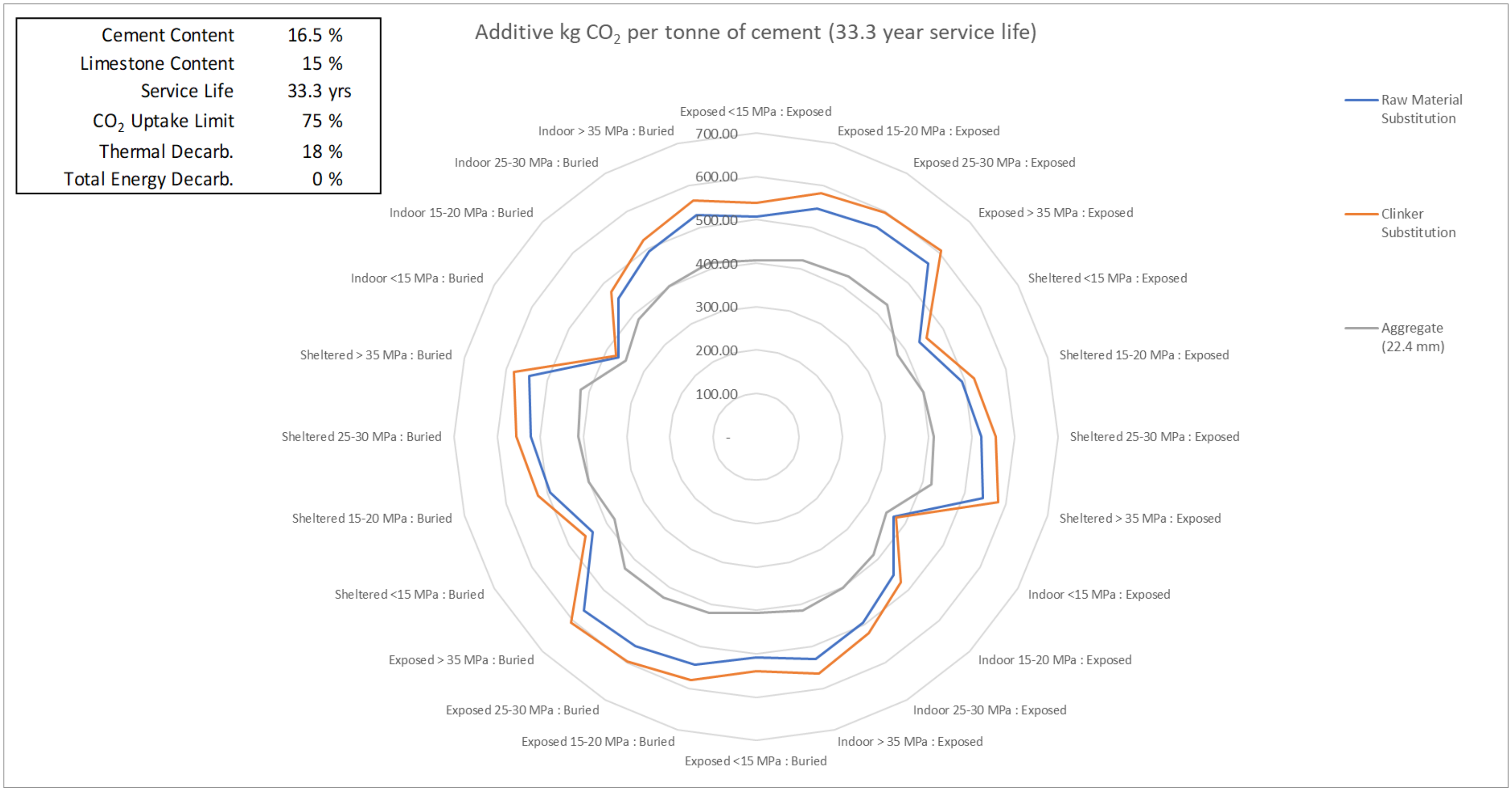


*Figure 7.48: Limestone Addition & Thermal Energy Decarbonization – 33.3 year service life*

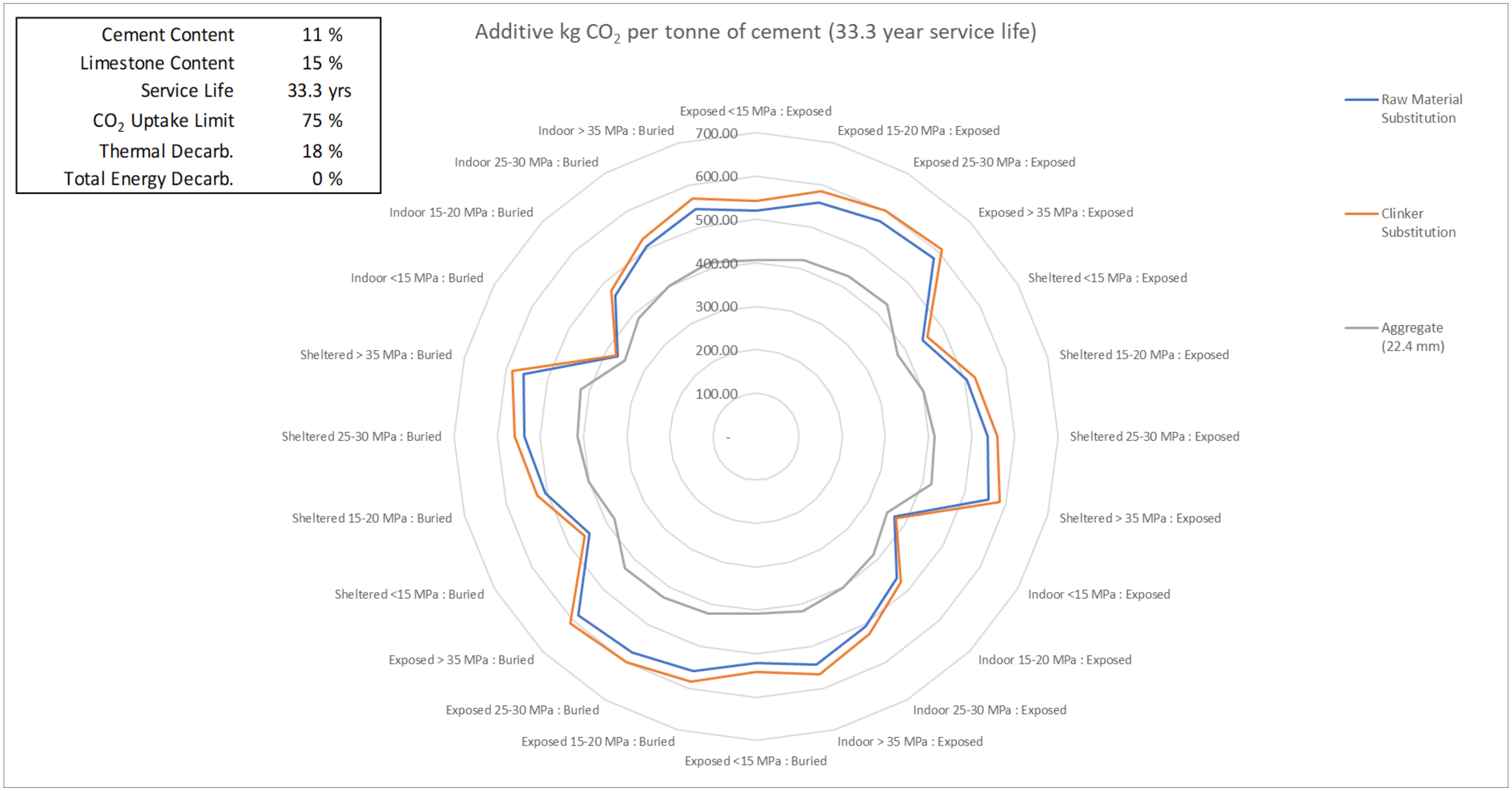


*Figure 7.49: Limestone Addition & Thermal Energy Decarbonization – 33.3 year service life*

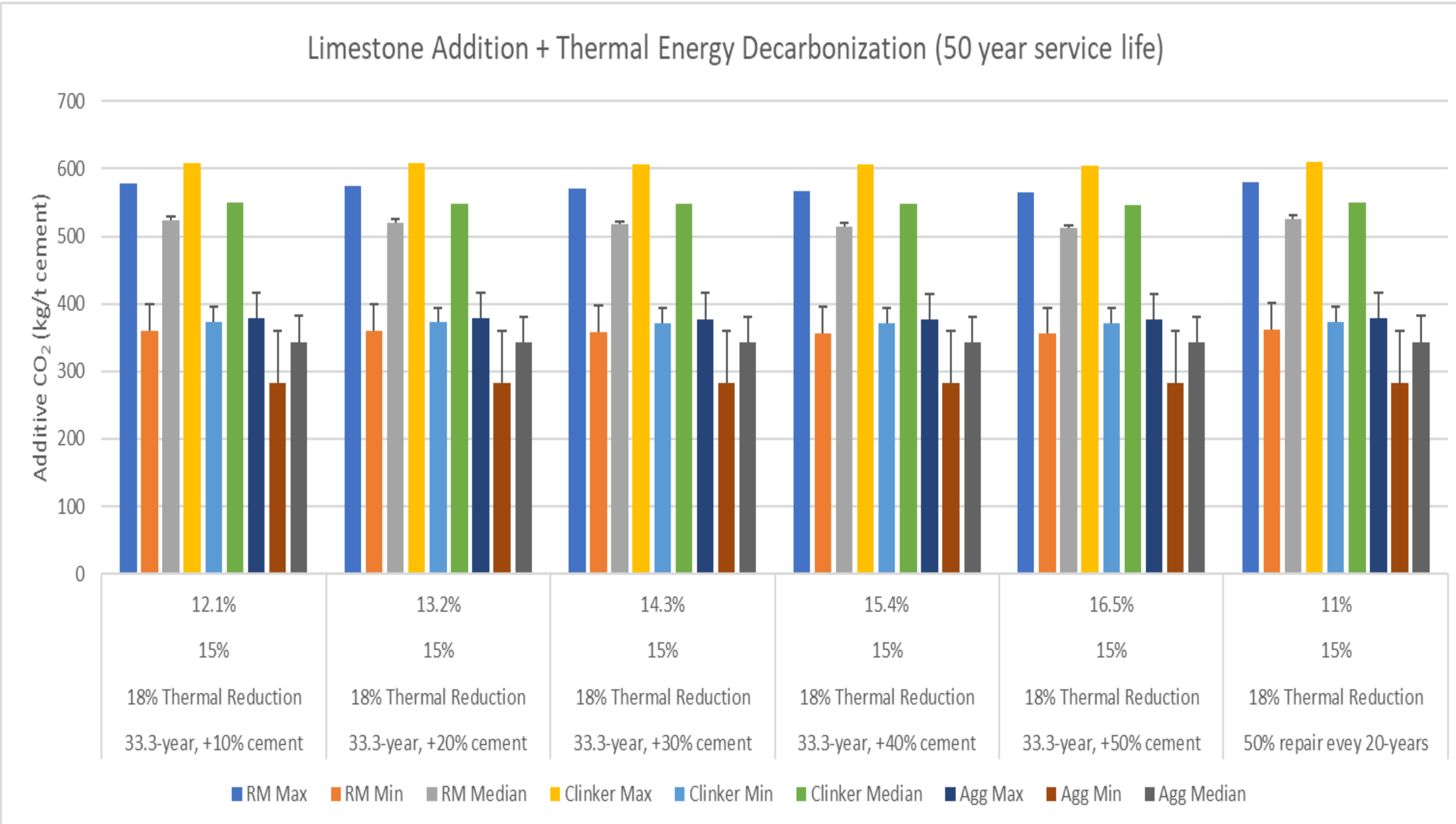


*Figure 7.50: Limestone Addition & Thermal Energy Decarbonization – 50 year service life*

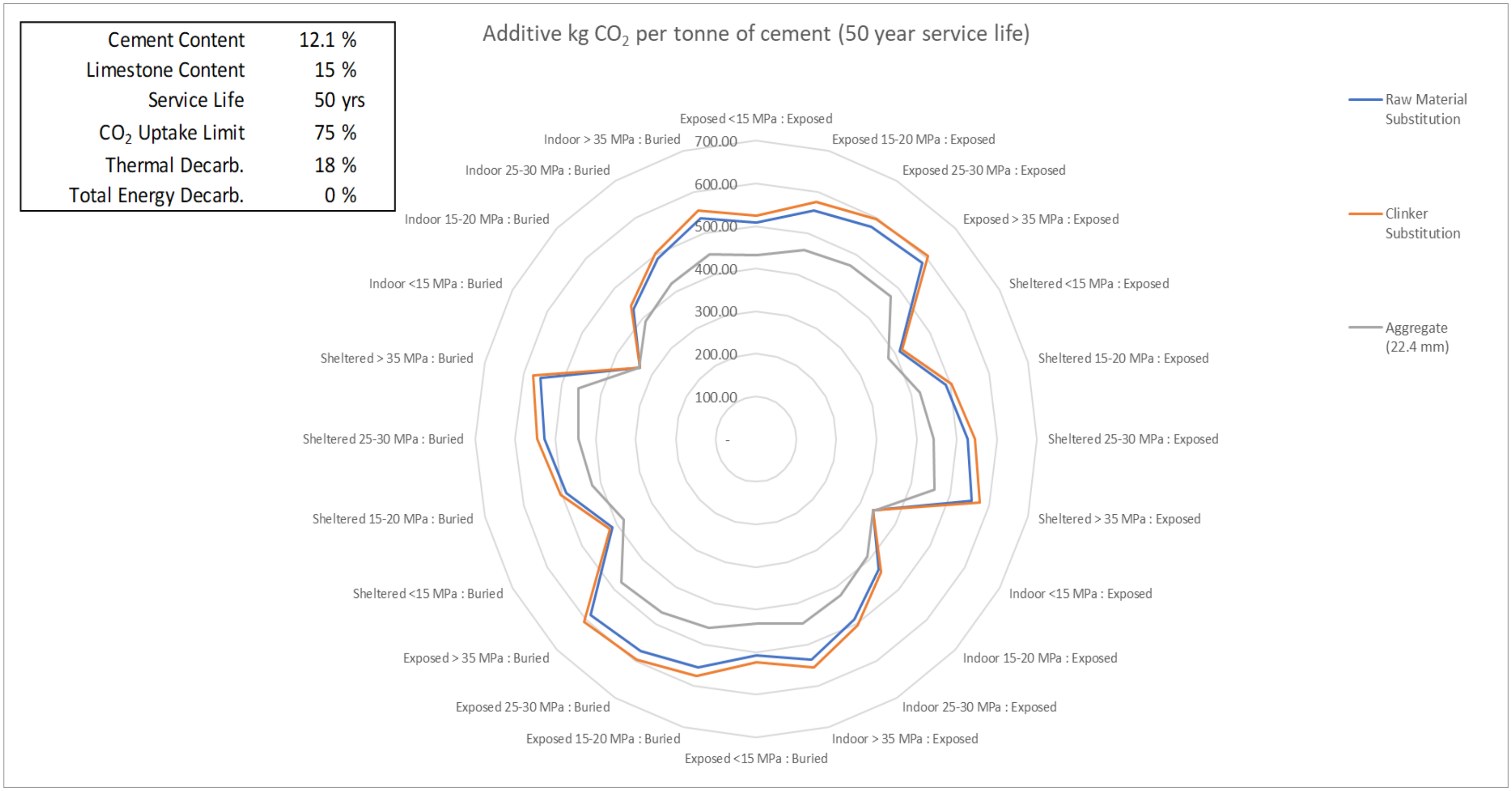


*Figure 7.51: Limestone Addition & Thermal Energy Decarbonization – 50 year service life*

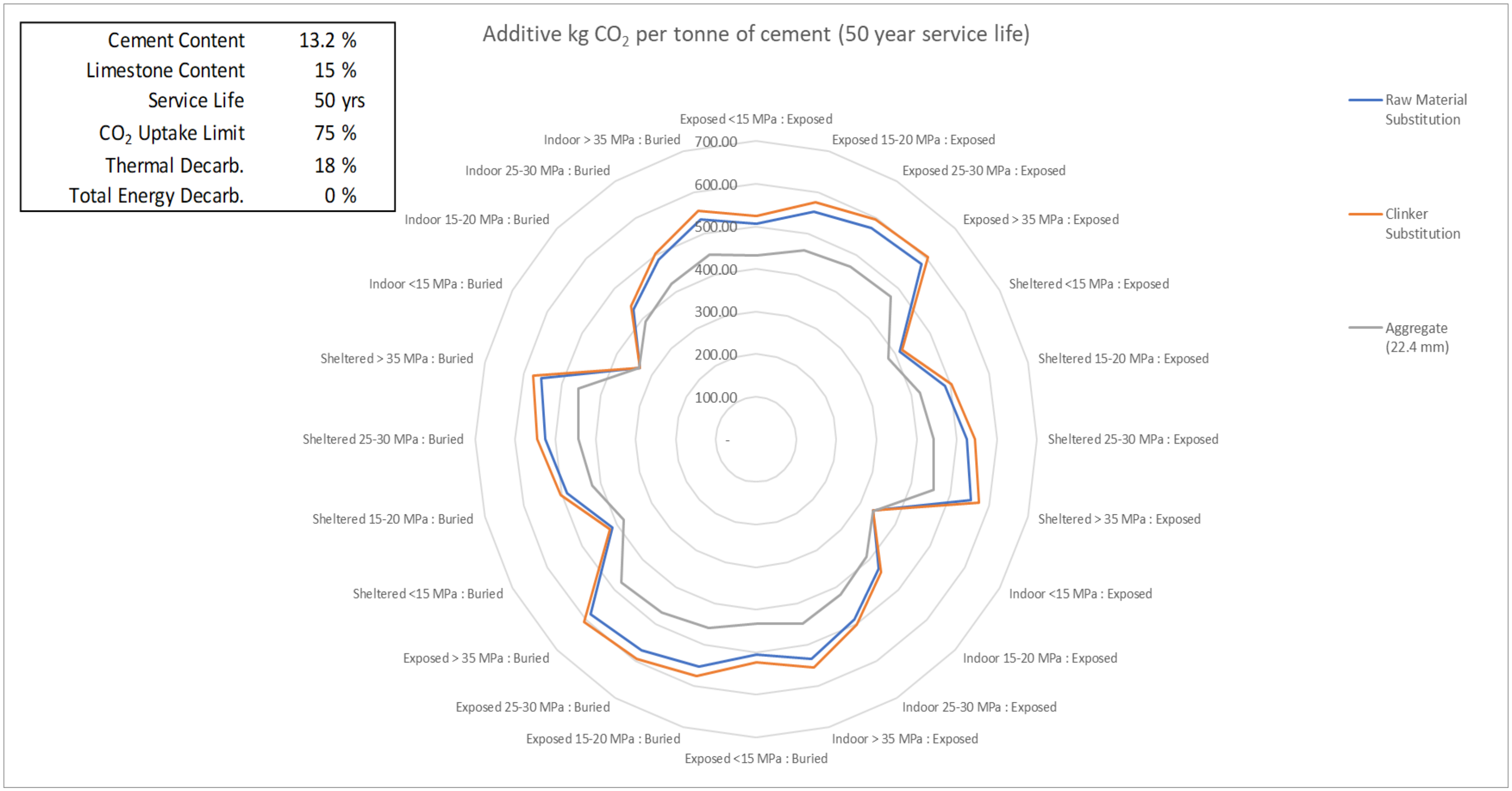


*Figure 7.52: Limestone Addition & Thermal Energy Decarbonization – 50 year service life*

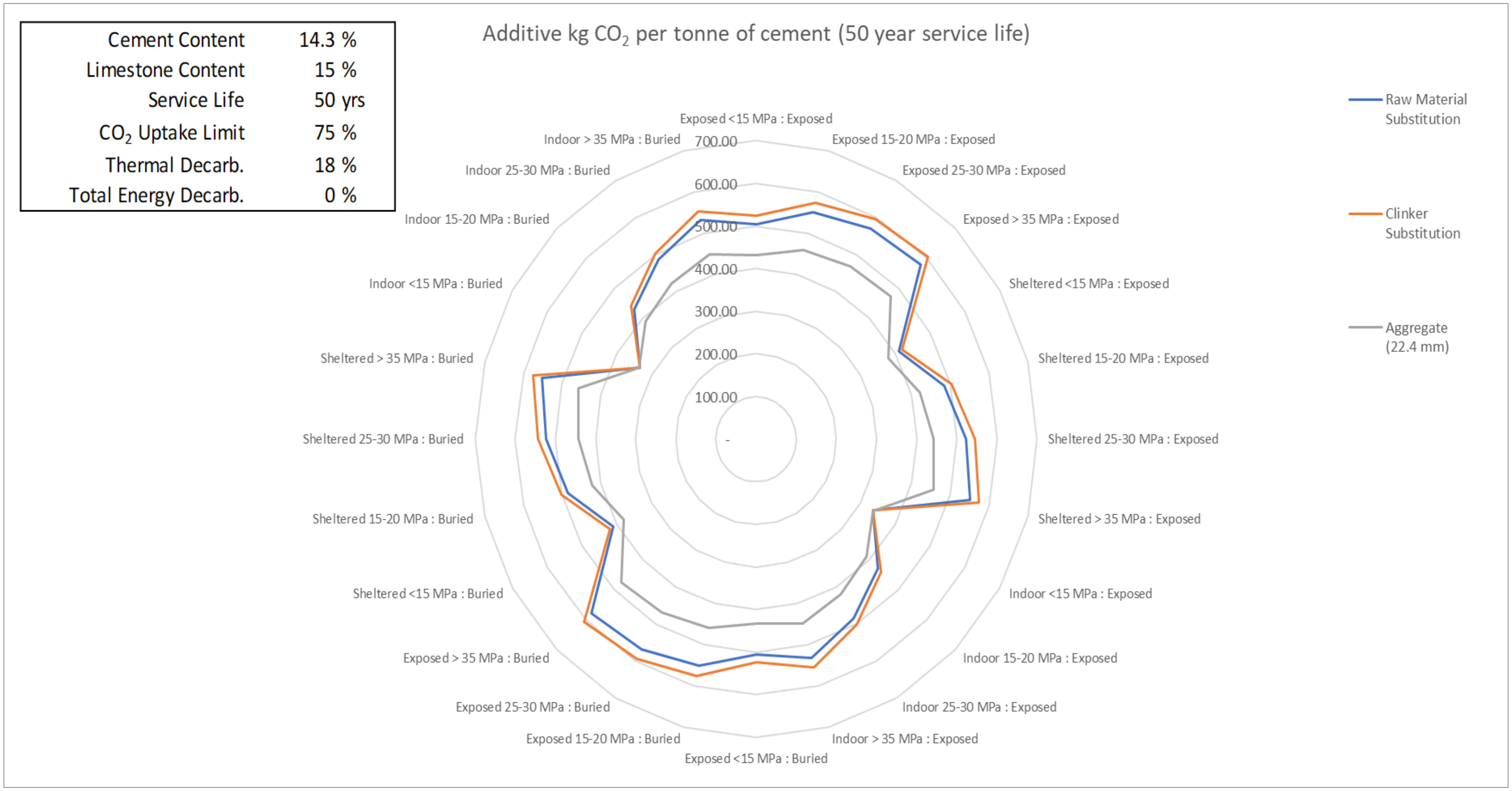


*Figure 7.53: Limestone Addition & Thermal Energy Decarbonization – 50 year service life*

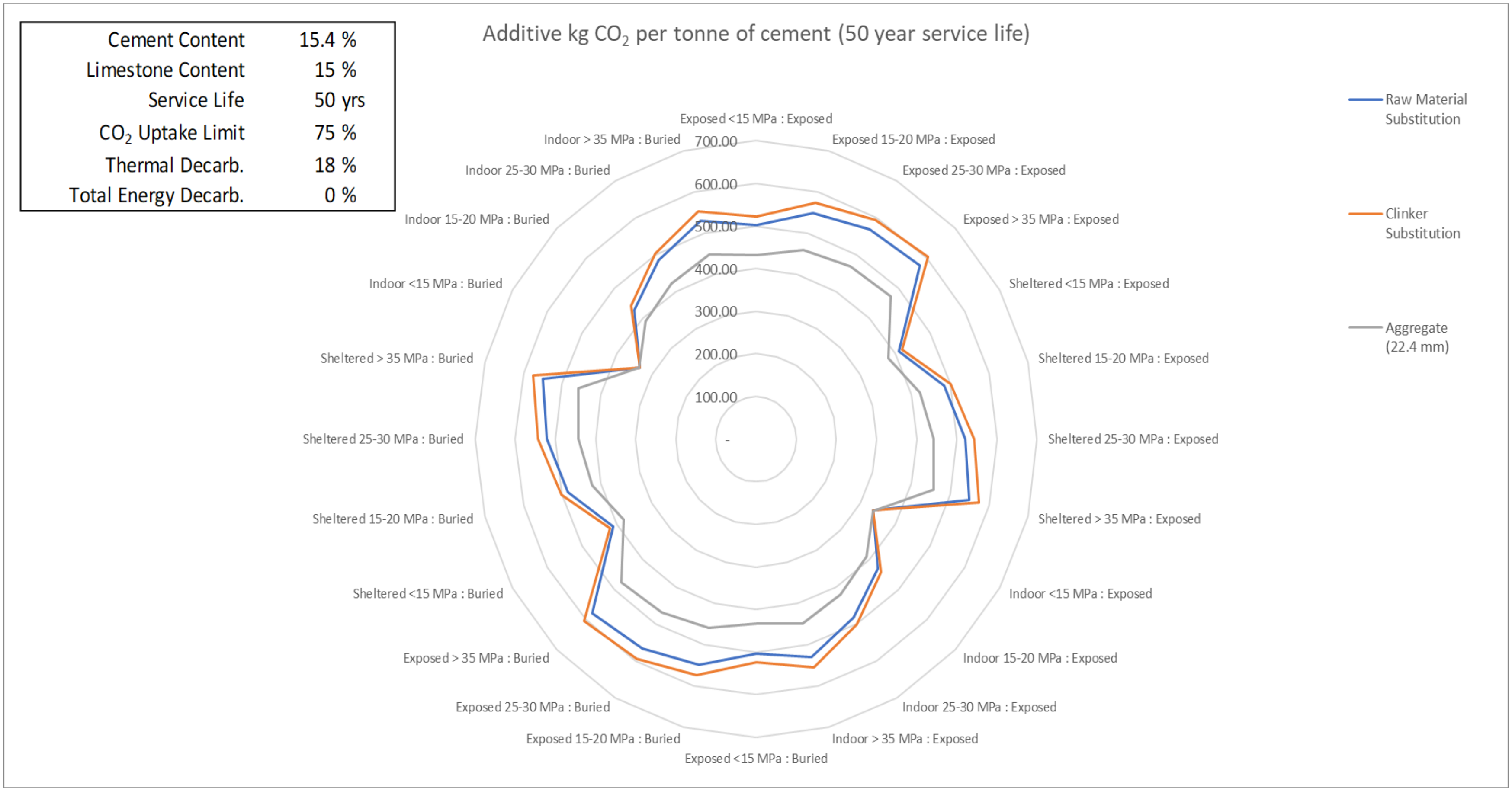


*Figure 7.54: Limestone Addition & Thermal Energy Decarbonization – 50 year service life*

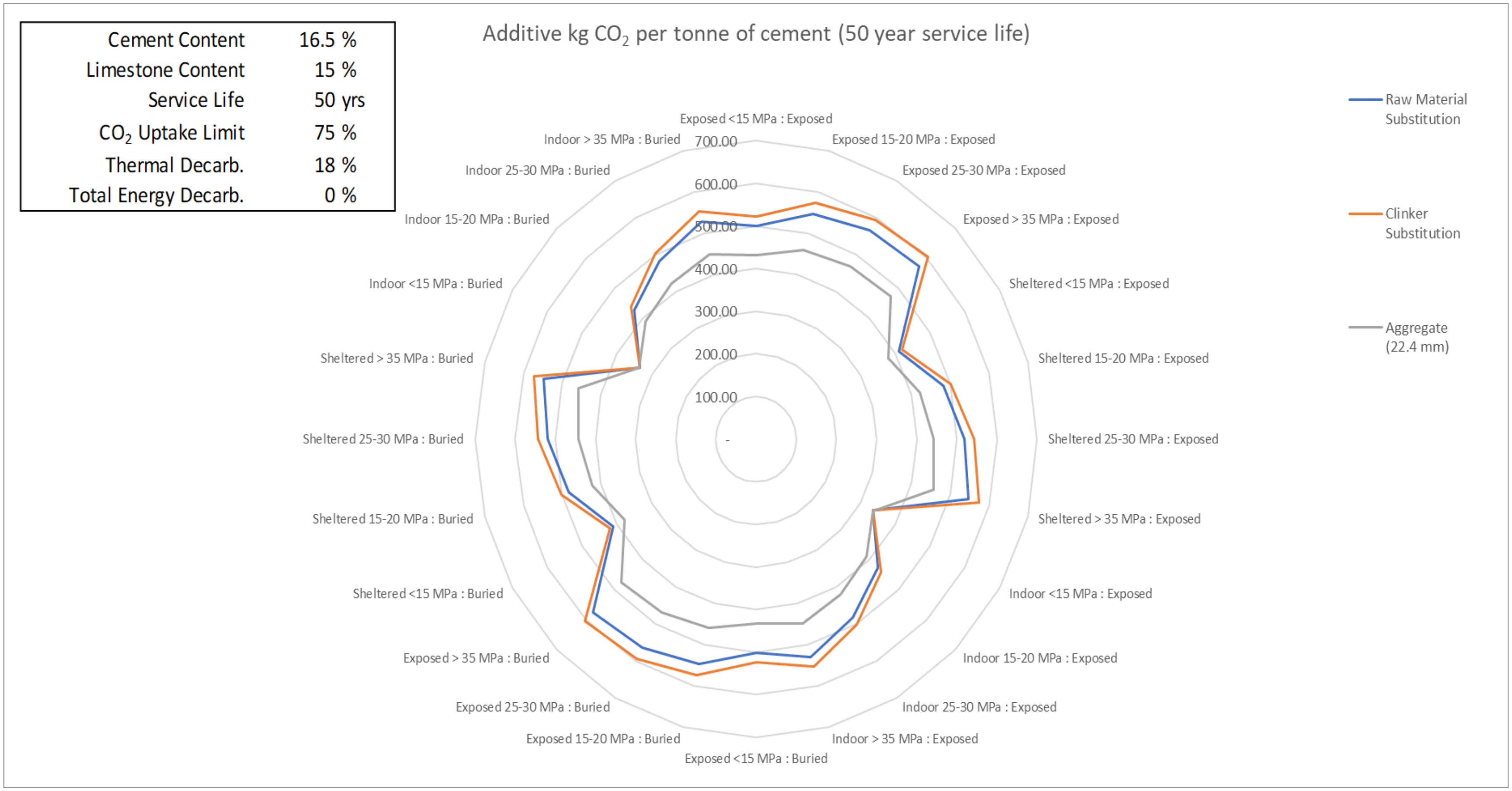


*Figure 7.55: Limestone Addition & Thermal Energy Decarbonization – 50 year service life*

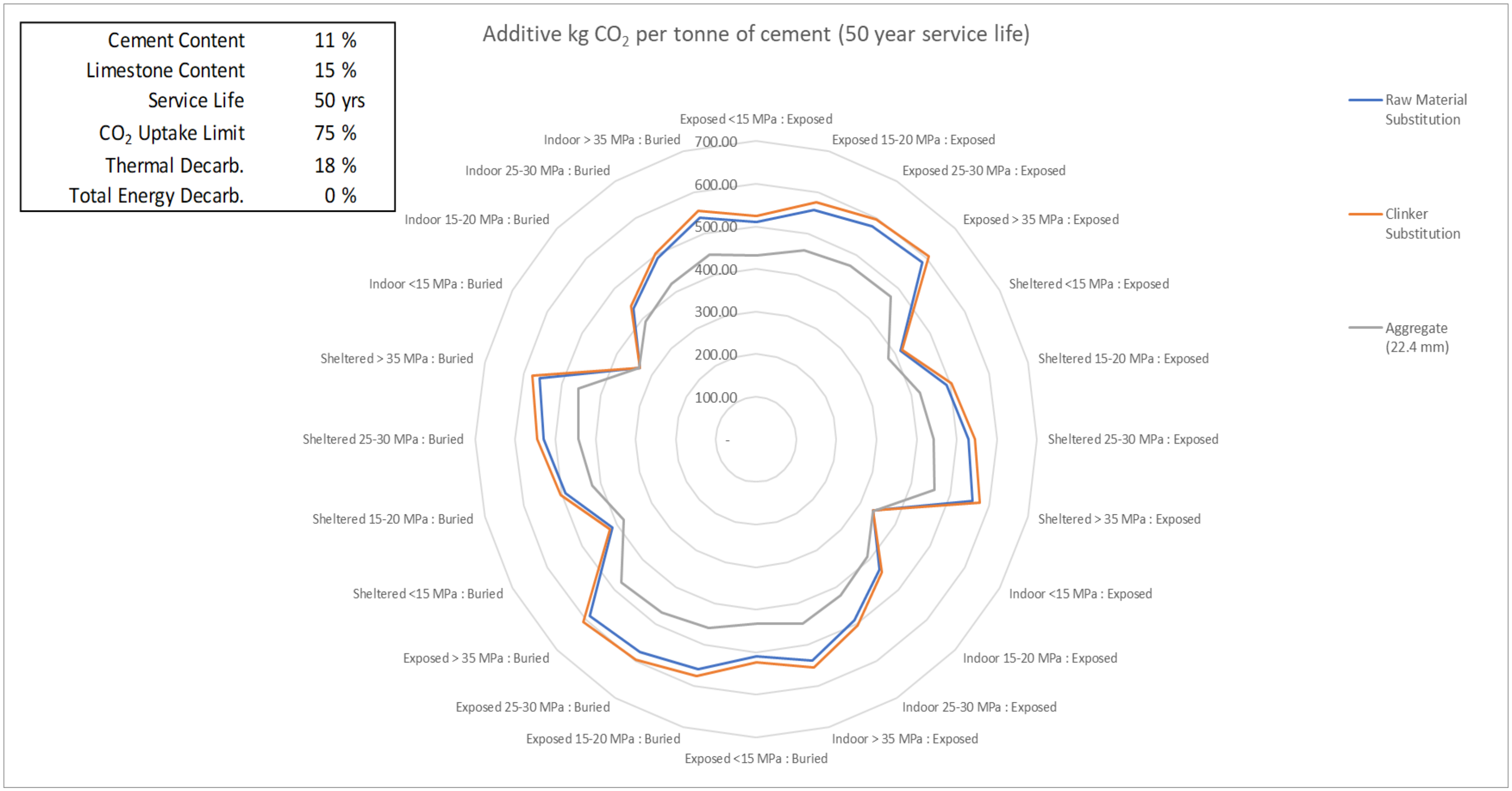


*Figure 7.56: Limestone Addition & Thermal Energy Decarbonization – 50 year service life*

### 7.7.1 Results and Interpretation of Limestone Addition (15%) + Thermal Decarbonization (18%)

The Limestone Addition (15%) and Thermal Decarbonization (18%) scenarios result in a range between 308 and 584 kg $CO_2$/t cement with raw material substitution, a 25-60% reduction from the baseline production emission of 771 kg $CO_2$/t cement. The range represents the variation created by concrete applications and associated carbon dioxide update. Clinker substitution values are slightly higher, between 315 and 608 kg $CO_2$/t cement. This shows that a significant reduction can be achieved while respecting material circularity.

The Canadian cement industry would have to achieve an average carbon capture and storage of approximately 450 kg $CO_2$/tonne cement in order to reach carbon neutrality and maintain material circularity at 18% thermal energy reduction and 15% limestone substitution with raw material substitution. Considering the utilization of EOL concrete for aggregates, the Canadian cement industry would have to achieve an average carbon capture and storage of approximately 340 kg $CO_2$/tonne cement in order to reach carbon neutrality.

These values could be further lowered, reducing the need for carbon capture and storage (CCS), with the adoption of the EU limestone standards as well as complete energy decarbonization. This scenario, presented in Section 7.8, represents the expected maximum potential for Avoidance.

## 7.8 EU Limestone Addition + Complete Energy Decarbonization

Figure 7.57 shows the results of maximum, minimum and median additive carbon dioxide emissions associated with complete energy decarbonization and limestone addition at 35% (EU regulatory limit)(Cement Association of Canada, 2020). The results also highlight the potential error for each scenario as mentioned in Section 7.3 and are illustrated with the error bars in the graphs. The additive carbon dioxide emissions for each type of application and concrete strength as detailed in Section 7.2 are presented in Figures 7.58 through 7.62 for a 50-year service life.

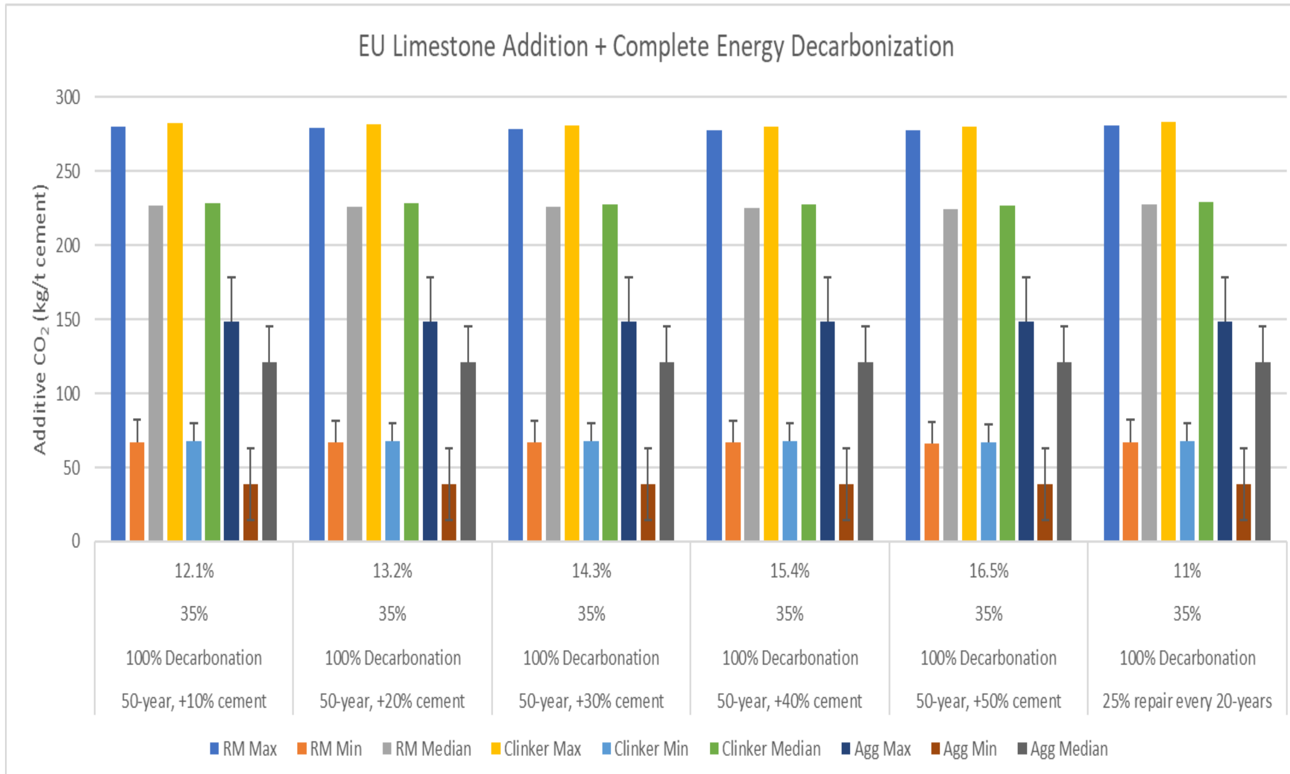


*Figure 7.57: EU Limestone Addition & Complete Energy Decarbonization – 50 year service life*

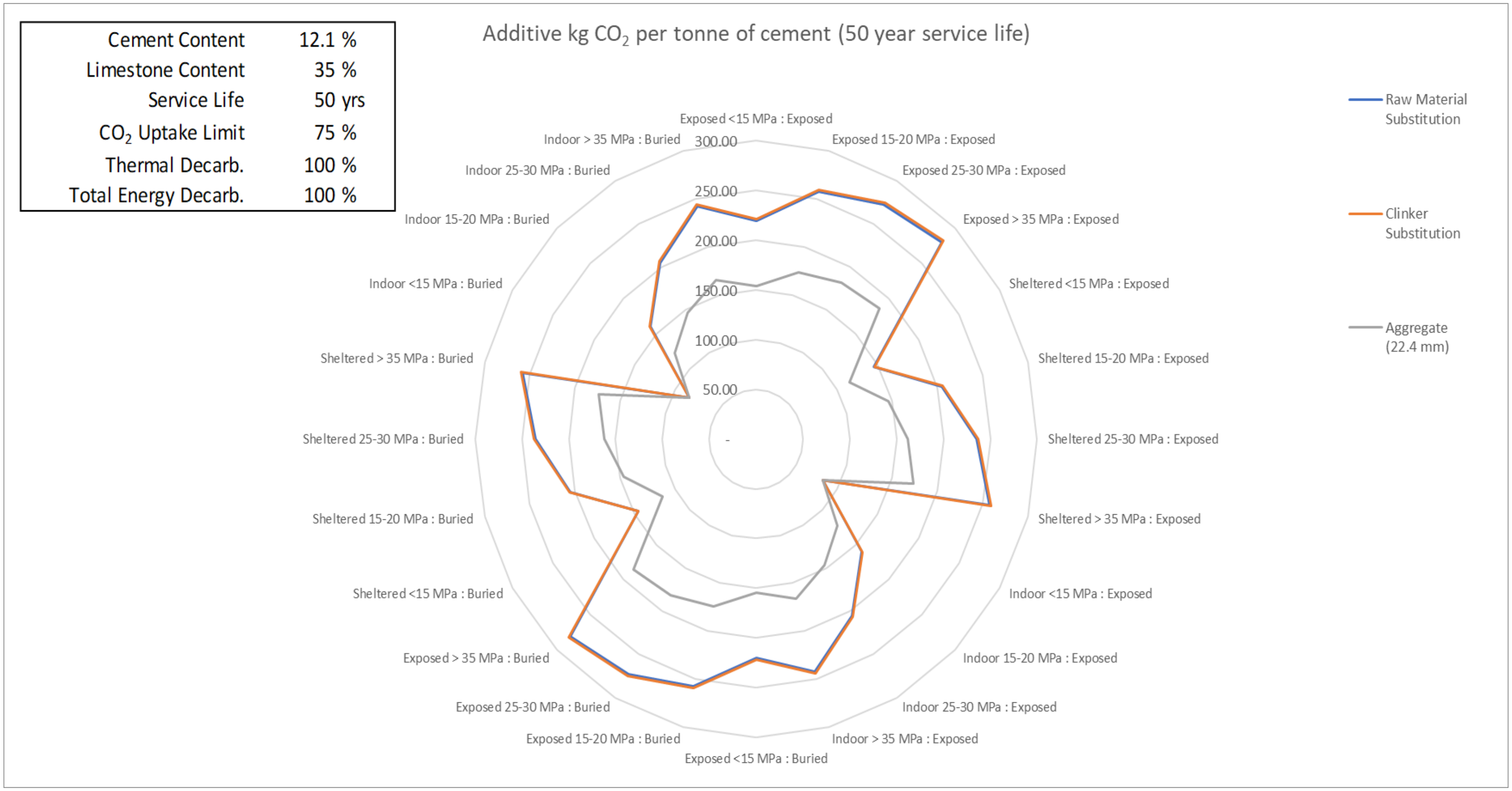


*Figure 7.58: EU Limestone Addition & Complete Energy Decarbonization – 50 year service life*

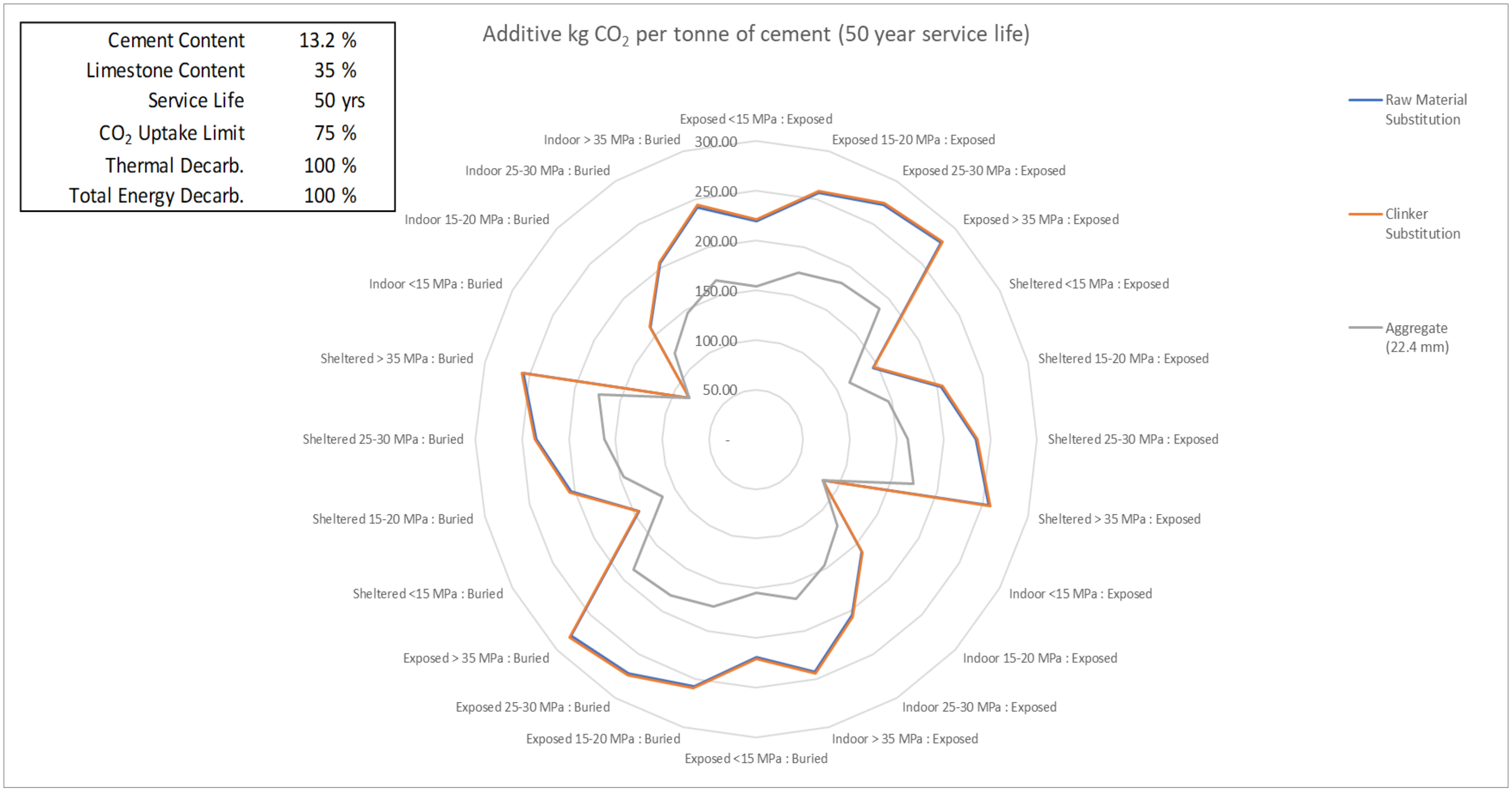


*Figure 7.59: EU Limestone Addition & Complete Energy Decarbonization – 50 year service life*

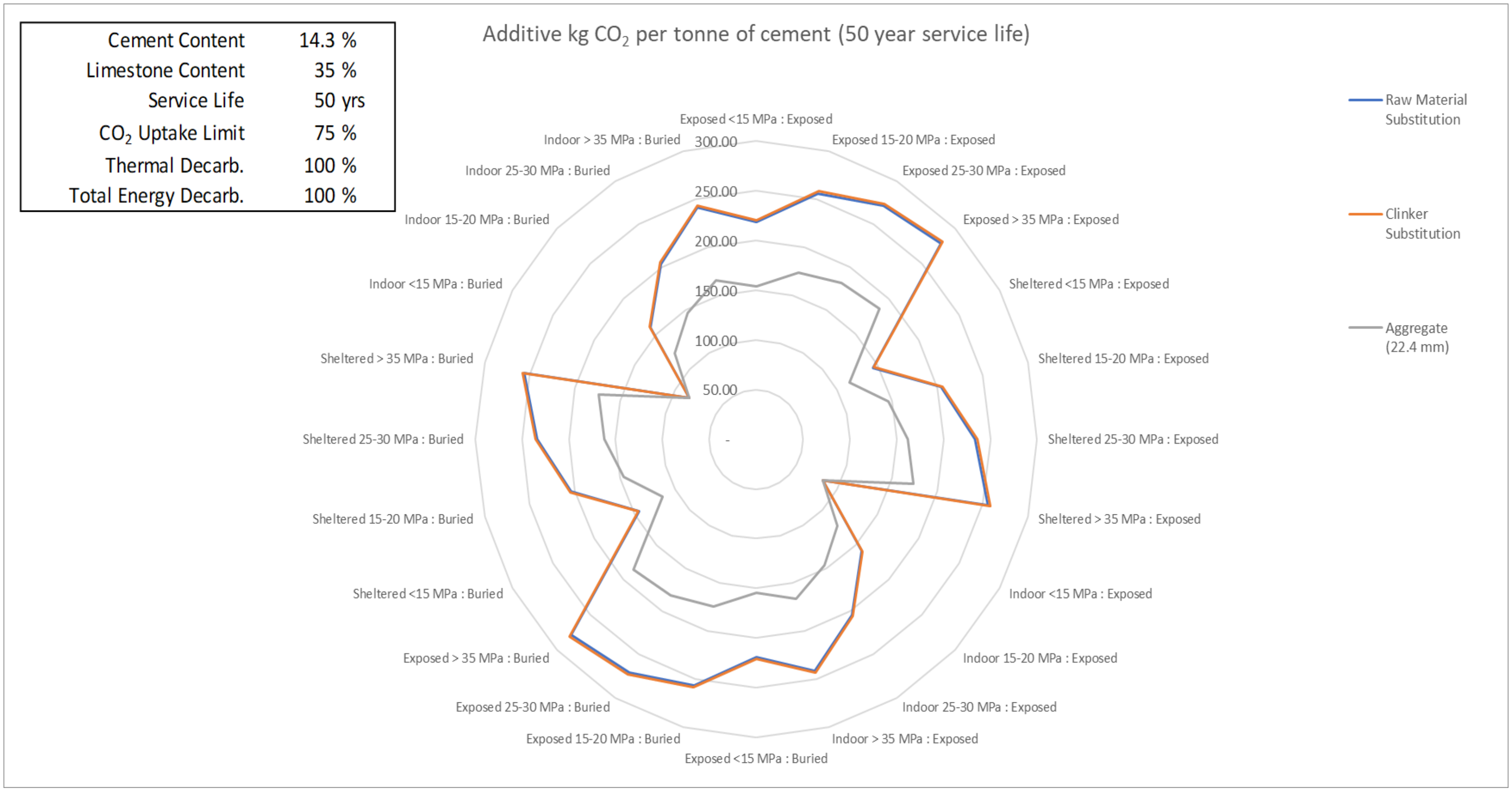


*Figure 7.60: EU Limestone Addition & Complete Energy Decarbonization – 50 year service life*

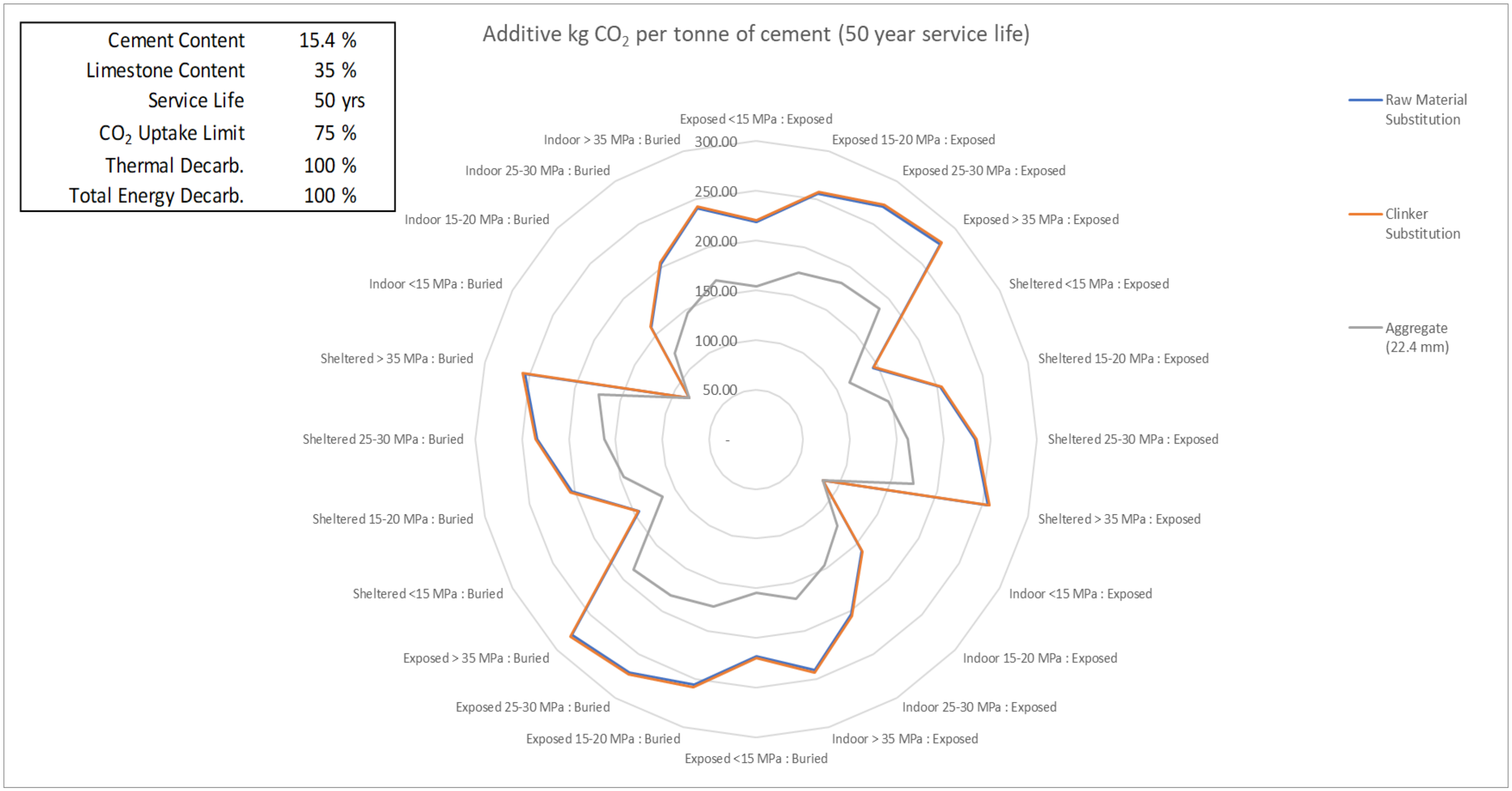


*Figure 7.61: EU Limestone Addition & Complete Energy Decarbonization – 50 year service life*

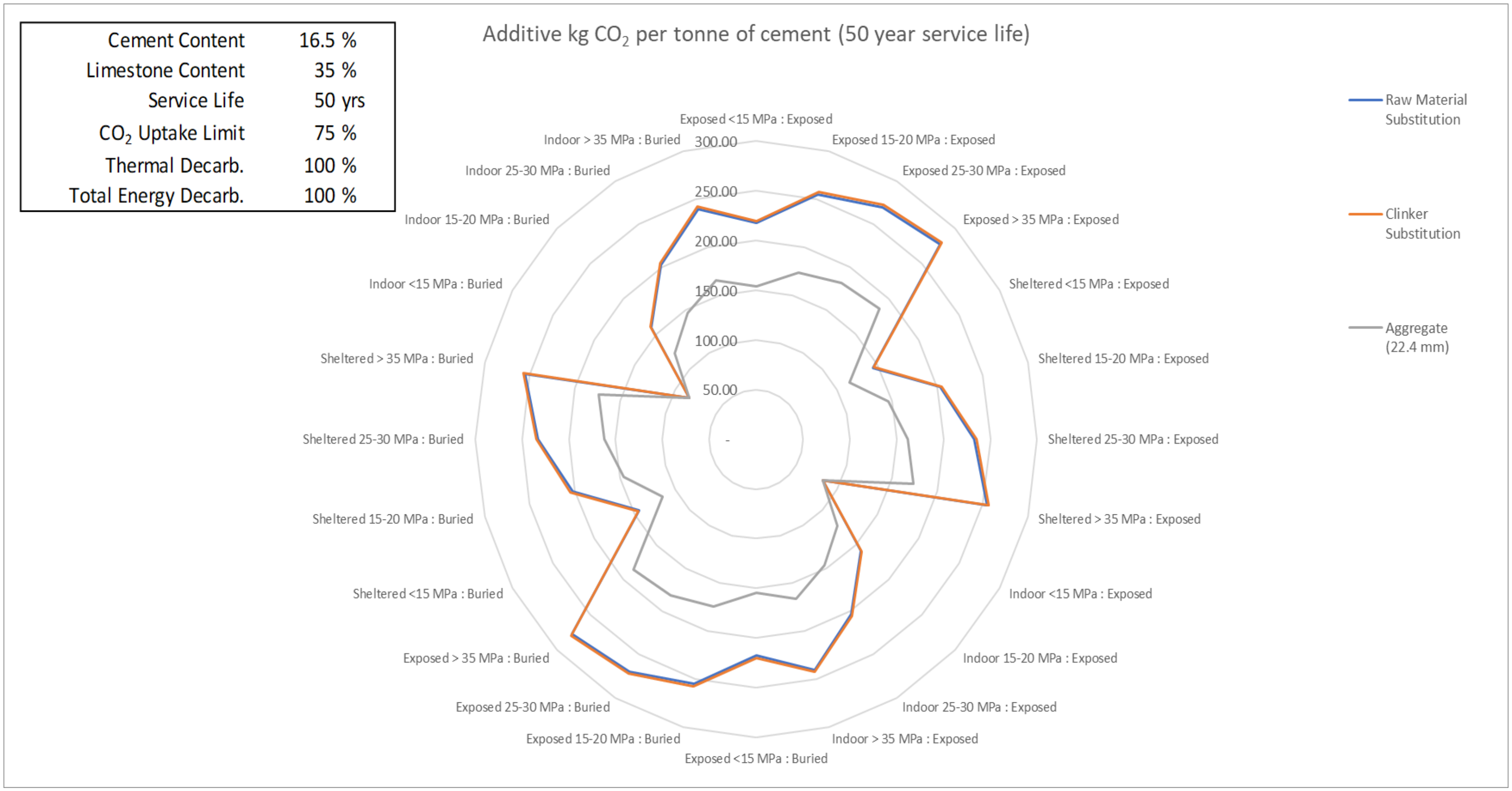


*Figure 7.62: EU Limestone Addition & Complete Energy Decarbonization – 50 year service life*

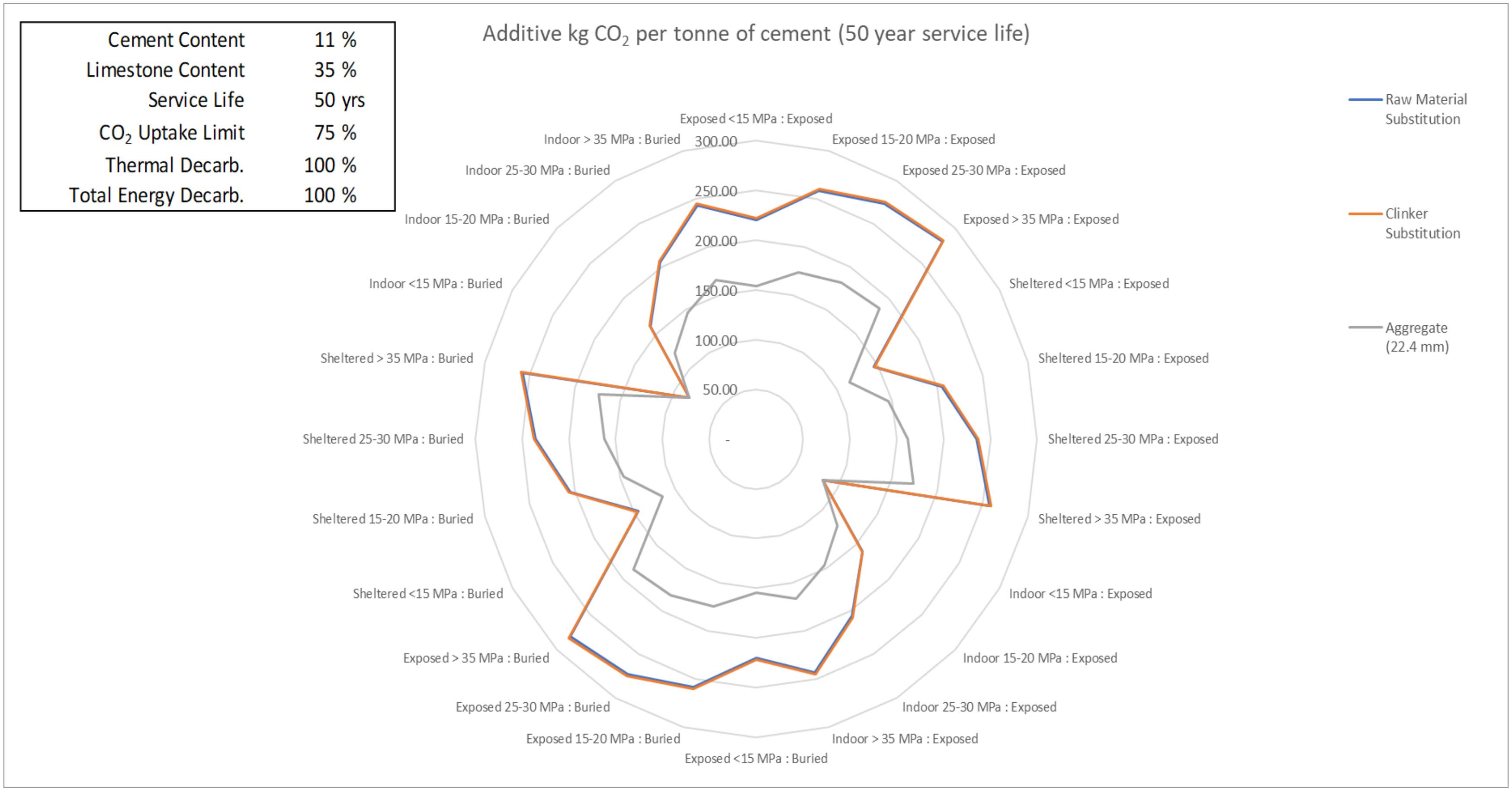


*Figure 7.63: EU Limestone Addition & Complete Energy Decarbonization – 50 year service life*

## 7.9 Overall Assessment for Canada & Conclusion

Figures 7.63 and 7.64 show the overall assessment for Canada based on the Carbon Hierarchy. This assessment is used to identify the full potential of each stage of the Carbon Hierarchy and highlight the minimum gap that the cement industry must close to reach carbon neutrality. Figure 7.63 shows the results of the 50-year additive carbon dioxide emissions assessment based on an 18% thermal reduction and 15% limestone addition. Figure 7.64 shows the results of additive carbon dioxide emissions assessment for a 50-year service life based on complete decarbonization and 35% limestone addition.

The outer ring of the radar graph shows the potential reduction that can be achieved through Avoidance. This is consistent regardless of the concrete strength as this reflects a reduction of impact and associated $CO_2$ emissions during cement manufacturing.

The next ring, Stretch, reflects the potential reductions associated with material circularity utilizing end of life concrete as a raw material.[1] Based on Figure 7.63, the Canadian cement industry would have to achieve carbon capture and storage between 311 and 586 kg $CO_2$/tonne cement in order to reach carbon neutrality and maintain material circularity at 18% thermal energy reduction and 15% limestone substitution. Looking to Figure 7.64, that gap is between 67 and 280 kg $CO_2$/tonne of cement with a fully decarbonated energy system and 35% limestone substitution. These values include the carbon dioxide uptake associated with cement.

The following ring, Sequester, represents the potential use of EOL concrete as aggregates that continues to uptake $CO_2$ during the secondary use. This ring no longer represents material circularity but is a valid level in the carbon hierarchy. Based on Figure 7.63, the Canadian cement industry would have to achieve carbon capture and storage between 277 and 425 kg $CO_2$/tonne cement in order to reach carbon neutrality utilizing carbon capture and utilization (CCU) at 18% thermal energy reduction and 15% limestone substitution. Looking to Figure 7.64, that gap is between 39 and 148 kg $CO_2$/tonne of cement with a fully decarbonated energy system and 35% limestone substitution.

These results highlight that the Carbon Hierarchy logically reduces additive carbon with each level. This also highlights that with the current best-case scenario of thermal energy reduction and limestone addition – the cement industry needs to reduce an additional 378 kg of $CO_2$ per tonne of cement production on average. Even in the scenario of complete energy decarbonization and 35% limestone addition (if EU standards are adopted) – the cement industry will need to capture and store or offset an average of 113 kg of $CO_2$ per tonne of cement produced.

The critical finding of the assessment is this chapter is that the Carbon Hierarchy can be used to empirically quantify the gap to reach carbon neutrality. The output provides clear results at each stage of the Carbon Hierarchy for the Canadian cement industry to reduce its additive carbon dioxide emissions.

[1] It should be noted that in all scenario, raw material substitution outperformed clinker substitution

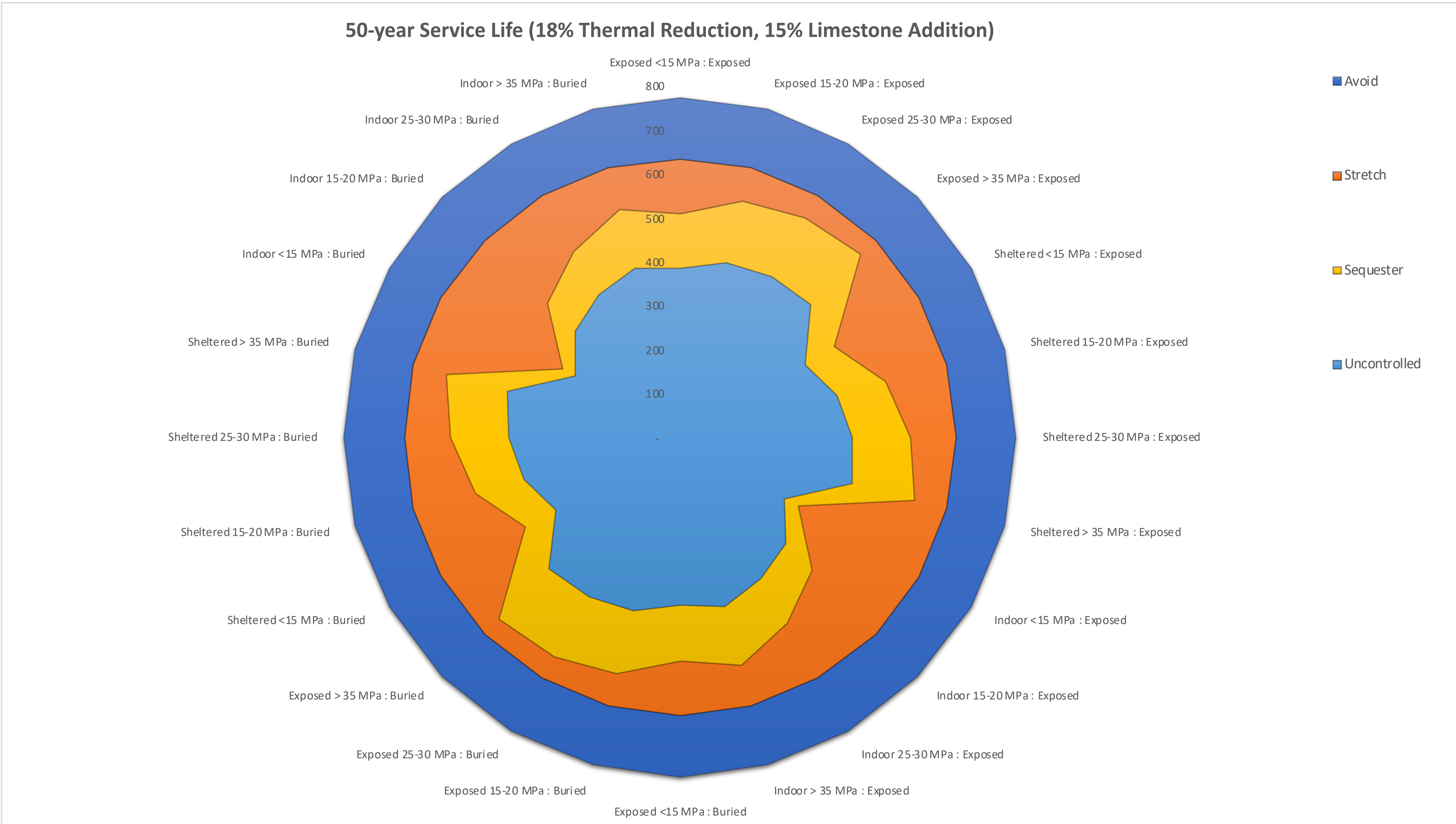


*Figure 7.64: Carbon Hierarchy Assessment: Canadian Cement Industry (15% limestone, 18% thermal reduction)*

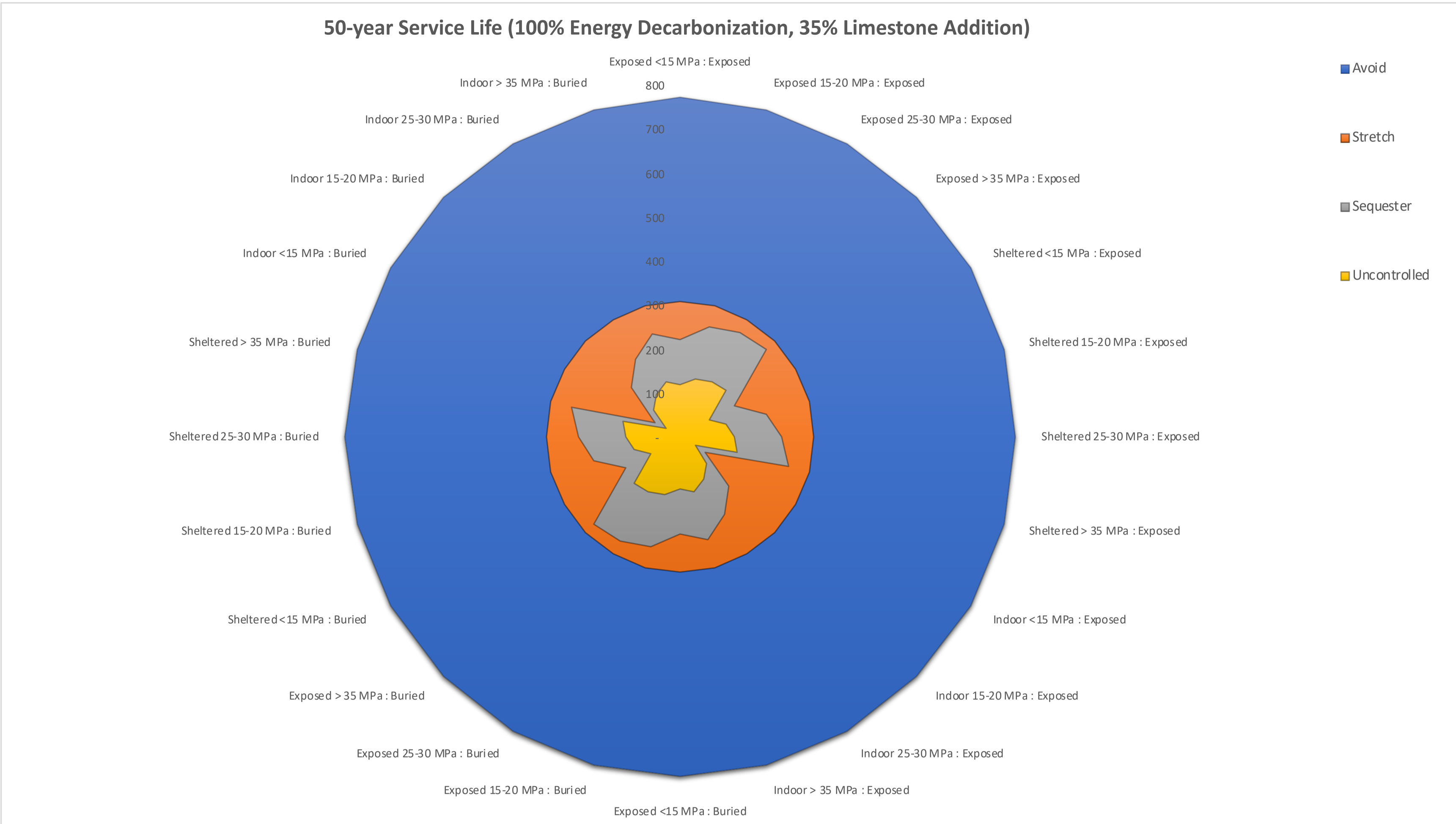


*Figure 7.65: Carbon Hierarchy Assessment: Canadian Cement Industry (35% limestone, complete energy decarb.)*

# Chapter 8

# Conclusions & Future Research

The concluding chapter discusses the value and limitation of the proposed carbon hierarchy as well as potential future research to expand on the concept. Ultimately, the value of this work is the creation and validation of a successive stage hierarchy for practitioners or policymakers to address greenhouse gas emission reduction for cement manufacturing that incorporates the concepts of circularity. The analytical model allows for empirical validation of the carbon hierarchy and quantifies the gap to reach carbon neutrality for the cement industry.

Further research is recommended for industrial symbiosis in the cement industry; application of the carbon hierarchy to other industries; and the potential application to environmental impacts beyond climate change that may be part of a lifecycle assessment.

### 8.1 Summary of Findings and Applicability

The International Panel for Climate Change (IPCC) reported in 2018 that anthropogenic greenhouse gas emissions must be reduced to net zero levels by 2050 to avoid irreversible impacts associated with global temperature increase of two degrees Celsius above pre-industrial levels (IPCC, 2018; UNFCCC, 2019). The cement industry represents nearly 8% of fossil fuel and industrial emissions, making it a key area of focus for policymakers around the world (OECD/IEA and The World Business Council for Sustainable Development, 2010) (Portland Cement Association, 2013)

In reviewing the existing academic research, numerous carbon mitigation strategies were identified for the cement sector with some reference to prioritization: however, the rationale for the prioritization is not clearly quantified. The review of existing research finds that the key concepts, strategies, and calculations have been identified for both carbon mitigation and circularity in the cement sector. What is fundamentally missing is an empirically validated strategy that considers all levers for carbon reduction in a systematic hierarchy while respecting material circularity as a core tenet.

The Carbon Hierarchy (Figure 1) is proposed as a successive stage hierarchy to address the gap identified in the existing research as no meaningful approach currently exists for practitioners or policymakers to address greenhouse gas emission reduction for cement manufacturing that incorporates the concepts of circularity. The logical and empirical validation of the hierarchy was tested with a model incorporating: life extension, thermal energy decarbonization, limestone substitution, mineral component (MIC) use in the form of blast furnace slag (BFS), carbon dioxide uptake and three end-of-life (EOL) pathways: raw material substitution; clinker substitution; and aggregate use.

A generalized model was tested and demonstrated that each level of the hierarchy is logical – resulting in reduction at each level while reducing material conservation for efforts that were successively lower on the hierarchy. A detailed empirical model was tested for Canadian cement manufacturing showing that material circularity and, in turn *Stretching*, was a valid stage of the Carbon Hierarchy for which carbon dioxide reductions could be quantified and material circularity could be logically validated.

The Canadian cement industry assessment showed that *Stretching* - ensuring material circularity by utilizing end-of-life concrete as a raw material would reduce additive $CO_2$ emissions from 633 kg $CO_2$/tonne of cement from *Avoidance* alone to between 311 and 586 kg $CO_2$/tonne cement. As such, *Stretching* represents a potential reduction of 7 to 50% of $CO_2$ emissions while respecting material conservation. This high variability is due to the type of concrete application and associated carbon dioxide uptake. These values highlight the potential to reduce additive carbon dioxide emissions and resource consumption simultaneously – proving that *a successive stage hierarchy for carbon mitigation and material circularity can be created that would ensure rational carbon reduction and resource conservation decision-making in the cement industry.*

Further to this, by incorporating carbon capture and utilization (CCU) with aggregate use in the secondary service life of EOL concrete, this research proves that *such a system can be used to quantify* *the gap to reach carbon neutrality* by identifying a gap between 277 and 425 kg $CO_2$/tonne cement based on the aforementioned scenarios.

With the complete decarbonization of energy systems and adoption of EU limestone substitution standards, the Canadian cement industry could reach 67 to 280 kg $CO_2$ per tonne of cement while maintaining material circularity.

The ability to quantify the benefit of each level including carbon uptake and material circularity provides a powerful tool for cement producers and policymakers alike not only to understand the potential to reduce GHG emissions while respecting material conservation but also clearly establish the amount of carbon capture and storage that needs to be dedicated to reach carbon neutrality for the cement industry.

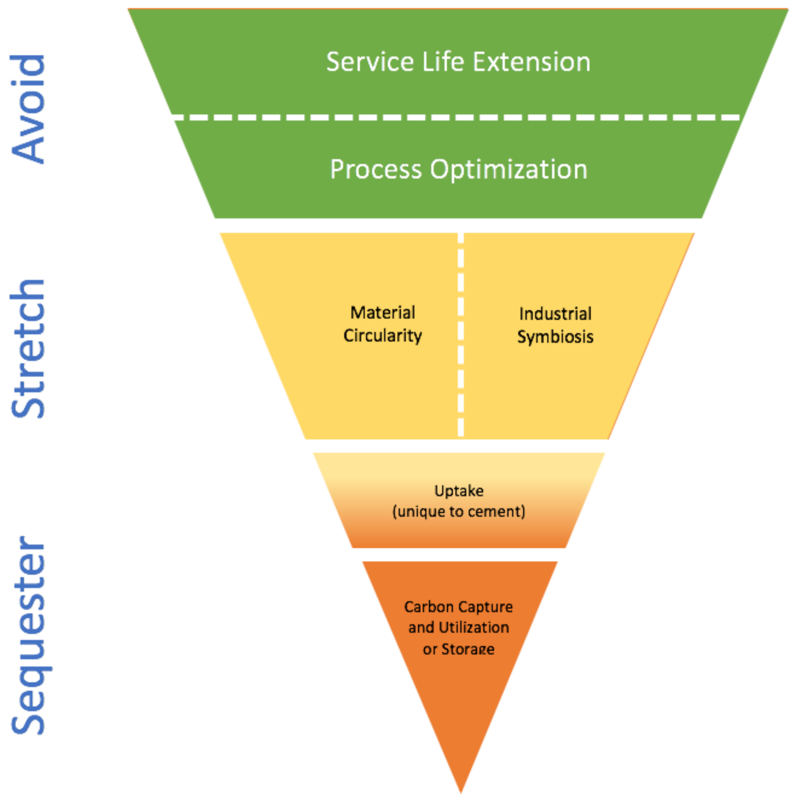


*Figure 8.1: Carbon Hierarchy*

### 8.2 Application Across Industry, Media and Future Research

The Carbon Hierarchy presented in this research is designed to be flexible in order to apply across industries. The model developed is limited to the cement industry. However, the logical structure of the hierarchy may be applicable to other energy intensive material industries. The concept of *Avoid,* whether through service life extension or process optimization is quite logical. Carbon capture utilization and storage (CCUS) are also well-established concepts and research areas (as demonstrated in Chapter 2) which represents *Sequester*. The original concept of *Stretch* and the formation of the successive stage hierarchy allows for practitioners and policymakers to approach carbon neutrality with material circularity in mind. Further to this, the ability to quantify the benefit of each step allows the determination of capital that should be invested in carbon capture and storage.

The Carbon Hierarchy should be tested for application to other industries to determine which levers would lead to maximum carbon reduction and the remaining gap for each industry to reach carbon neutrality. Further to this, industrial symbiosis should be evaluated in greater detail to determine the best opportunities for material exchanges amongst industries. Industrial symbiosis quantification could further enhance the ability of lifecycle assessment (at a macro level) to establish processes for jurisdictional rather than industry scale decision-making to reach carbon neutrality and further reduce the need for carbon capture and storage.

The Carbon Hierarchy has demonstrated the opportunity to adopt a well-established, logical concept – the Waste Hierarchy – to assess a different sustainability challenge; namely climate change. The potential exists for similar approaches to be adopted across other environmental impacts such as water management and non-GHG air emissions. The specific nomenclature of the hierarchy will likely change for different applications, but the potential exists to validate and communicate a clear successive stage hierarchy for decisionmakers to address other environmental challenges.

Additional future research into material reintroduction in lifecycle assessment would be beneficial to better capture material circularity, end-of-life used and industrial symbiosis. This research should focus on carbon footprinting as a priority to support climate change decision-making but could be expanded to other media in lifecycle assessment.

This research has highlighted the ability to prioritize the carbon dioxide mitigation strategies in a simplified hierarchy understandable to both industry practitioners and policymakers. The Carbon Hierarchy not only incorporates - but further quantifies – the greenhouse gas impact of material circularity. Most importantly, this research demonstrates the clear potential to empirically validate and order actions that meet both circular economy and climate change mitigation objectives.

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# Appendix A

## Uptake Error from Overlapping Surface Area

| **Depth (mm)** | **10** | **20** | **30** | **40** | **50** | **100** | **150** | **200** | **250** | **300** | **350** | **400** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Max Error (100 years) | 0.20% | 0.56% | 0.69% | 0.79% | 0.87% | 1.19% | 1.39% | 1.52% | 1.60% | 1.65% | 1.67% | 1.68% |
| Max Error (500 years) | 0.20% | 0.56% | 1.03% | 1.57% | 1.96% | 2.66% | 3.11% | 3.40% | 3.58% | 3.69% | 3.75% | 3.76% |

| | **% error per mm of k value** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10 years | 0.1% | 0.2% | 0.2% | 0.2% | 0.3% | 0.4% | 0.4% | 0.5% | 0.5% | 0.5% | 0.5% | 0.5% |
| 20 years | 0.2% | 0.3% | 0.3% | 0.4% | 0.4% | 0.5% | 0.6% | 0.7% | 0.7% | 0.7% | 0.7% | 0.8% |
| 30 years | | 0.3% | 0.4% | 0.4% | 0.5% | 0.7% | 0.8% | 0.8% | 0.9% | 0.9% | 0.9% | 0.9% |
| 40 years | | 0.4% | 0.4% | 0.5% | 0.6% | 0.8% | 0.9% | 1.0% | 1.0% | 1.0% | 1.1% | 1.1% |
| 50 years | | 0.4% | 0.5% | 0.6% | 0.6% | 0.8% | 1.0% | 1.1% | 1.1% | 1.2% | 1.2% | 1.2% |
| 60 years | | 0.4% | 0.5% | 0.6% | 0.7% | 0.9% | 1.1% | 1.2% | 1.2% | 1.3% | 1.3% | 1.3% |
| 70 years | | 0.5% | 0.6% | 0.7% | 0.7% | 1.0% | 1.2% | 1.3% | 1.3% | 1.4% | 1.4% | 1.4% |
| 80 years | | 0.5% | 0.6% | 0.7% | 0.8% | 1.1% | 1.2% | 1.4% | 1.4% | 1.5% | 1.5% | 1.5% |
| 90 years | | 0.5% | 0.7% | 0.7% | 0.8% | 1.1% | 1.3% | 1.4% | 1.5% | 1.6% | 1.6% | 1.6% |
| 100 years | | 0.6% | 0.7% | 0.8% | 0.9% | 1.2% | 1.4% | 1.5% | 1.6% | 1.6% | 1.7% | 1.7% |

| **Depth (mm)** | **450** | **500** | **550** | **600** | **650** | **700** | **750** | **800** | **850** | **900** | **950** | **1000** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Max Error (100 years) | 1.67% | 1.66% | 1.63% | 1.61% | 1.57% | 1.54% | 1.51% | 1.47% | 1.44% | 1.40% | 1.37% | 1.33% |
| Max Error (500 years) | 3.74% | 3.71% | 3.66% | 3.59% | 3.52% | 3.45% | 3.37% | 3.29% | 3.22% | 3.14% | 3.06% | 2.98% |

| | **% error per mm of k value** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10 years | 0.5% | 0.5% | 0.5% | 0.5% | 0.5% | 0.5% | 0.5% | 0.5% | 0.5% | 0.4% | 0.4% | 0.4% |
| 20 years | 0.7% | 0.7% | 0.7% | 0.7% | 0.7% | 0.7% | 0.7% | 0.7% | 0.6% | 0.6% | 0.6% | 0.6% |
| 30 years | 0.9% | 0.9% | 0.9% | 0.9% | 0.9% | 0.8% | 0.8% | 0.8% | 0.8% | 0.8% | 0.7% | 0.7% |
| 40 years | 1.1% | 1.0% | 1.0% | 1.0% | 1.0% | 1.0% | 1.0% | 0.9% | 0.9% | 0.9% | 0.9% | 0.8% |
| 50 years | 1.2% | 1.2% | 1.2% | 1.1% | 1.1% | 1.1% | 1.1% | 1.0% | 1.0% | 1.0% | 1.0% | 0.9% |
| 60 years | 1.3% | 1.3% | 1.3% | 1.2% | 1.2% | 1.2% | 1.2% | 1.1% | 1.1% | 1.1% | 1.1% | 1.0% |
| 70 years | 1.4% | 1.4% | 1.4% | 1.3% | 1.3% | 1.3% | 1.3% | 1.2% | 1.2% | 1.2% | 1.1% | 1.1% |
| 80 years | 1.5% | 1.5% | 1.5% | 1.4% | 1.4% | 1.4% | 1.3% | 1.3% | 1.3% | 1.3% | 1.2% | 1.2% |
| 90 years | 1.6% | 1.6% | 1.5% | 1.5% | 1.5% | 1.5% | 1.4% | 1.4% | 1.4% | 1.3% | 1.3% | 1.3% |
| 100 years | 1.7% | 1.7% | 1.6% | 1.6% | 1.6% | 1.5% | 1.5% | 1.5% | 1.4% | 1.4% | 1.4% | 1.3% |

Appendix B

Number of years to reach full recarbonation of one cubic meter of concrete with and without for overlapping penetration

| | | | Depth (mm) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Concrete Strength | Type of Exposure | k value | 10 | 20 | 30 | 40 | 50 | 100 | 150 | 200 | 250 | 300 | 350 | 400 | 450 | 500 |
| Indoor | <15 MPa | 15 | 0 | 0 | 1 | 2 | 3 | 10 | 20 | 32 | 44 | 57 | 68 | 78 | 87 | 95 |
| Sheltered | <15 MPa | 10 | 0 | 1 | 2 | 4 | 6 | 22 | 45 | 72 | 100 | 127 | 153 | 176 | 197 | 214 |
| Indoor | 15-20 MPa | 9 | 0 | 1 | 3 | 5 | 7 | 27 | 56 | 89 | 123 | 157 | 189 | 218 | 243 | 265 |
| Sheltered | 15-20 MPa | 6 | 1 | 3 | 6 | 11 | 17 | 61 | 125 | 200 | 278 | 354 | 425 | 490 | 547 | 596 |
| Indoor | 25-30 MPa | 6 | 1 | 3 | 6 | 11 | 17 | 61 | 125 | 200 | 278 | 354 | 425 | 490 | 547 | 596 |
| Exposed | <15 MPa | 5 | 1 | 4 | 9 | 16 | 24 | 88 | 181 | 288 | 400 | 510 | 613 | 705 | 787 | 858 |
| Sheltered | 25-30 MPa | 4 | 2 | 6 | 14 | 24 | 37 | 138 | 282 | 450 | 625 | 797 | 957 | 1102 | 1230 | 1340 |
| Indoor | >35 MPa | 3.5 | 2 | 8 | 18 | 32 | 49 | 181 | 369 | 587 | 816 | 1040 | 1250 | 1440 | 1607 | 1751 |
| Buried | <15 MPa | 3 | 3 | 11 | 24 | 43 | 66 | 246 | 502 | 799 | 1111 | 1416 | 1702 | 1960 | 2187 | 2383 |
| Exposed | 15-20 MPa | 2.5 | 4 | 16 | 35 | 62 | 96 | 354 | 722 | 1151 | 1600 | 2039 | 2450 | 2822 | 3149 | 3431 |
| Sheltered | >35 MPa | 2.5 | 4 | 16 | 35 | 62 | 96 | 354 | 722 | 1151 | 1600 | 2039 | 2450 | 2822 | 3149 | 3431 |
| Wet | <15 MPa | 2 | 6 | 25 | 55 | 97 | 149 | 553 | 1129 | 1799 | 2500 | 3186 | 3829 | 4409 | 4921 | 5362 |
| Buried | 15-20 MPa | 1.5 | 11 | 44 | 98 | 172 | 266 | 983 | 2007 | 3198 | 4444 | 5665 | 6806 | 7839 | 8748 | 9532 |
| Exposed | 25-30 MPa | 1.5 | 11 | 44 | 98 | 172 | 266 | 983 | 2007 | 3198 | 4444 | 5665 | 6806 | 7839 | 8748 | 9532 |
| Wet | 15-20 MPa | 1 | 25 | 99 | 220 | 388 | 598 | 2211 | 4515 | 7195 | 10000 | 12746 | 15314 | 17637 | 19683 | 21447 |
| Buried | 25-30 MPa | 1 | 25 | 99 | 220 | 388 | 598 | 2211 | 4515 | 7195 | 10000 | 12746 | 15314 | 17637 | 19683 | 21447 |
| Exposed | >35 MPa | 1 | 25 | 99 | 220 | 388 | 598 | 2211 | 4515 | 7195 | 10000 | 12746 | 15314 | 17637 | 19683 | 21447 |
| Wet | 25-30 MPa | 0.75 | 44 | 176 | 392 | 689 | 1063 | 3931 | 8026 | 12792 | 17778 | 22659 | 27226 | 31355 | 34993 | 38127 |
| Buried | >35 MPa | 0.75 | 44 | 176 | 392 | 689 | 1063 | 3931 | 8026 | 12792 | 17778 | 22659 | 27226 | 31355 | 34993 | 38127 |
| Wet | >35 MPa | 0.5 | 100 | 396 | 882 | 1550 | 2392 | 8846 | 18060 | 28782 | 40000 | 50984 | 61258 | 70549 | 78733 | 85786 |

*Number of years to reach full recarbonation of 1 $m^3$ of concrete*

| | | | Depth (mm) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Concrete Strength** | **Type of Exposure** | **k value** | **550** | **600** | 650 | 700 | 750 | 800 | 850 | 900 | 950 | 1000 |
| Indoor | <15 MPa | 15 | 102 | 107 | 112 | 115 | 118 | 120 | 122 | 123 | 123 | 123 |
| Sheltered | <15 MPa | 10 | 229 | 242 | 252 | 260 | 266 | 271 | 274 | 276 | 277 | 278 |
| Indoor | 15-20 MPa | 9 | 283 | 298 | 311 | 321 | 328 | 334 | 338 | 341 | 342 | 343 |
| Sheltered | 15-20 MPa | 6 | 637 | 671 | 699 | 722 | 739 | 752 | 761 | 767 | 771 | 772 |
| Indoor | 25-30 MPa | 6 | 637 | 671 | 699 | 722 | 739 | 752 | 761 | 767 | 771 | 772 |
| Exposed | <15 MPa | 5 | 917 | 967 | 1007 | 1039 | 1064 | 1083 | 1096 | 1105 | 1110 | 1111 |
| Sheltered | 25-30 MPa | 4 | 1434 | 1511 | 1574 | 1624 | 1663 | 1692 | 1713 | 1726 | 1734 | 1736 |
| Indoor | >35 MPa | 3.5 | 1872 | 1973 | 2056 | 2121 | 2172 | 2210 | 2237 | 2255 | 2265 | 2268 |
| Buried | <15 MPa | 3 | 2549 | 2686 | 2798 | 2887 | 2956 | 3008 | 3045 | 3069 | 3082 | 3086 |
| Exposed | 15-20 MPa | 2.5 | 3670 | 3868 | 4029 | 4157 | 4257 | 4332 | 4385 | 4419 | 4439 | 4444 |
| Sheltered | >35 MPa | 2.5 | 3670 | 3868 | 4029 | 4157 | 4257 | 4332 | 4385 | 4419 | 4439 | 4444 |
| Wet | <15 MPa | 2 | 5734 | 6043 | 6295 | 6496 | 6651 | 6768 | 6851 | 6905 | 6935 | 6944 |
| Buried | 15-20 MPa | 1.5 | 10194 | 10744 | 11191 | 11548 | 11825 | 12032 | 12180 | 12276 | 12329 | 12346 |
| Exposed | 25-30 MPa | 1.5 | 10194 | 10744 | 11191 | 11548 | 11825 | 12032 | 12180 | 12276 | 12329 | 12346 |
| Wet | 15-20 MPa | 1 | 22937 | 24174 | 25181 | 25983 | 26605 | 27072 | 27404 | 27621 | 27741 | 27778 |
| Buried | 25-30 MPa | 1 | 22937 | 24174 | 25181 | 25983 | 26605 | 27072 | 27404 | 27621 | 27741 | 27778 |
| Exposed | >35 MPa | 1 | 22937 | 24174 | 25181 | 25983 | 26605 | 27072 | 27404 | 27621 | 27741 | 27778 |
| Wet | 25-30 MPa | 0.75 | 40777 | 42976 | 44766 | 46192 | 47299 | 48128 | 48719 | 49105 | 49317 | 49383 |
| Buried | >35 MPa | 0.75 | 40777 | 42976 | 44766 | 46192 | 47299 | 48128 | 48719 | 49105 | 49317 | 49383 |
| Wet | >35 MPa | 0.5 | 91748 | 96695 | 100723 | 103931 | 106422 | 108288 | 109617 | 110486 | 110964 | 111111 |

*Number of years to reach full recarbonation of 1 $m^3$ of concrete*

| | | | Depth (mm) | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Concrete Strength | Type of Exposure | k value | 10 | 20 | 30 | 40 | 50 | 100 | 150 | 200 | 250 | 300 | 350 | 400 | 450 | 500 |
| Indoor | <15 MPa | 15 | 0 | 1 | 2 | 3 | 5 | 18 | 36 | 57 | 79 | 101 | 122 | 140 | 156 | 170 |
| Sheltered | <15 MPa | 10 | 0 | 1 | 3 | 6 | 9 | 32 | 65 | 104 | 144 | 184 | 221 | 255 | 284 | 310 |
| Indoor | 15-20 MPa | 9 | 0 | 2 | 4 | 7 | 10 | 38 | 77 | 123 | 171 | 218 | 262 | 302 | 337 | 368 |
| Sheltered | 15-20 MPa | 6 | 1 | 3 | 8 | 13 | 21 | 76 | 155 | 247 | 344 | 438 | 526 | 606 | 676 | 737 |
| Indoor | 25-30 MPa | 6 | 1 | 3 | 8 | 13 | 21 | 76 | 155 | 247 | 344 | 438 | 526 | 606 | 676 | 737 |
| Exposed | <15 MPa | 5 | 1 | 5 | 11 | 18 | 29 | 105 | 215 | 343 | 477 | 608 | 730 | 841 | 938 | 1022 |
| Sheltered | 25-30 MPa | 4 | 2 | 7 | 16 | 28 | 43 | 159 | 324 | 517 | 718 | 916 | 1100 | 1267 | 1414 | 1540 |
| Indoor | >35 MPa | 3.5 | 2 | 9 | 20 | 36 | 55 | 204 | 416 | 663 | 922 | 1175 | 1411 | 1625 | 1814 | 1976 |
| Buried | <15 MPa | 3 | 3 | 12 | 27 | 48 | 74 | 272 | 556 | 887 | 1232 | 1571 | 1887 | 2173 | 2425 | 2643 |
| Exposed | 15-20 MPa | 2.5 | 4 | 17 | 38 | 68 | 104 | 386 | 787 | 1254 | 1743 | 2222 | 2670 | 3075 | 3432 | 3739 |
| Sheltered | >35 MPa | 2.5 | 4 | 17 | 38 | 68 | 104 | 386 | 787 | 1254 | 1743 | 2222 | 2670 | 3075 | 3432 | 3739 |
| Wet | <15 MPa | 2 | 7 | 26 | 59 | 104 | 160 | 592 | 1209 | 1926 | 2677 | 3412 | 4099 | 4721 | 5269 | 5741 |
| Buried | 15-20 MPa | 1.5 | 12 | 46 | 103 | 181 | 280 | 1034 | 2112 | 3365 | 4677 | 5962 | 7163 | 8249 | 9206 | 10031 |
| Exposed | 25-30 MPa | 1.5 | 12 | 46 | 103 | 181 | 280 | 1034 | 2112 | 3365 | 4677 | 5962 | 7163 | 8249 | 9206 | 10031 |
| Wet | 15-20 MPa | 1 | 26 | 102 | 228 | 401 | 619 | 2288 | 4670 | 7443 | 10345 | 13185 | 15842 | 18245 | 20362 | 22186 |
| Buried | 25-30 MPa | 1 | 26 | 102 | 228 | 401 | 619 | 2288 | 4670 | 7443 | 10345 | 13185 | 15842 | 18245 | 20362 | 22186 |
| Exposed | >35 MPa | 1 | 26 | 102 | 228 | 401 | 619 | 2288 | 4670 | 7443 | 10345 | 13185 | 15842 | 18245 | 20362 | 22186 |
| Wet | 25-30 MPa | 0.75 | 45 | 180 | 402 | 707 | 1090 | 4032 | 8233 | 13120 | 18234 | 23241 | 27925 | 32160 | 35891 | 39107 |
| Buried | >35 MPa | 0.75 | 45 | 180 | 402 | 707 | 1090 | 4032 | 8233 | 13120 | 18234 | 23241 | 27925 | 32160 | 35891 | 39107 |
| Wet | >35 MPa | 0.5 | 101 | 402 | 897 | 1576 | 2433 | 8996 | 18367 | 29271 | 40681 | 51851 | 62300 | 71749 | 80073 | 87246 |

*Number of years to reach full recarbonation of 1 $m^3$ of concrete accounting for overlapping penetration*

| | | | Depth (mm) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Concrete Strength | Type of Exposure | k value | 550 | 600 | 650 | 700 | 750 | 800 | 850 | 900 | 950 | 1000 |
| Indoor | <15 MPa | 15 | 182 | 192 | 200 | 206 | 211 | 215 | 218 | 219 | 220 | 221 |
| Sheltered | <15 MPa | 10 | 331 | 349 | 364 | 375 | 384 | 391 | 396 | 399 | 401 | 401 |
| Indoor | 15-20 MPa | 9 | 393 | 414 | 431 | 445 | 456 | 464 | 470 | 473 | 475 | 476 |
| Sheltered | 15-20 MPa | 6 | 788 | 830 | 865 | 893 | 914 | 930 | 941 | 949 | 953 | 954 |
| Indoor | 25-30 MPa | 6 | 788 | 830 | 865 | 893 | 914 | 930 | 941 | 949 | 953 | 954 |
| Exposed | <15 MPa | 5 | 1093 | 1152 | 1200 | 1239 | 1268 | 1291 | 1306 | 1317 | 1322 | 1324 |
| Sheltered | 25-30 MPa | 4 | 1648 | 1736 | 1809 | 1866 | 1911 | 1945 | 1968 | 1984 | 1993 | 1995 |
| Indoor | >35 MPa | 3.5 | 2114 | 2228 | 2320 | 2394 | 2452 | 2495 | 2525 | 2545 | 2556 | 2560 |
| Buried | <15 MPa | 3 | 2826 | 2979 | 3103 | 3202 | 3278 | 3336 | 3377 | 3403 | 3418 | 3423 |
| Exposed | 15-20 MPa | 2.5 | 3999 | 4214 | 4390 | 4530 | 4638 | 4720 | 4778 | 4815 | 4836 | 4843 |
| Sheltered | >35 MPa | 2.5 | 3999 | 4214 | 4390 | 4530 | 4638 | 4720 | 4778 | 4815 | 4836 | 4843 |
| Wet | <15 MPa | 2 | 6140 | 6471 | 6741 | 6955 | 7122 | 7247 | 7336 | 7394 | 7426 | 7436 |
| Buried | 15-20 MPa | 1.5 | 10728 | 11307 | 11778 | 12153 | 12444 | 12662 | 12818 | 12919 | 12975 | 12992 |
| Exposed | 25-30 MPa | 1.5 | 10728 | 11307 | 11778 | 12153 | 12444 | 12662 | 12818 | 12919 | 12975 | 12992 |
| Wet | 15-20 MPa | 1 | 23728 | 25007 | 26049 | 26878 | 27522 | 28005 | 28349 | 28573 | 28697 | 28735 |
| Buried | 25-30 MPa | 1 | 23728 | 25007 | 26049 | 26878 | 27522 | 28005 | 28349 | 28573 | 28697 | 28735 |
| Exposed | >35 MPa | 1 | 23728 | 25007 | 26049 | 26878 | 27522 | 28005 | 28349 | 28573 | 28697 | 28735 |
| Wet | 25-30 MPa | 0.75 | 41824 | 44080 | 45915 | 47378 | 48513 | 49364 | 49970 | 50366 | 50584 | 50651 |
| Buried | >35 MPa | 0.75 | 41824 | 44080 | 45915 | 47378 | 48513 | 49364 | 49970 | 50366 | 50584 | 50651 |
| Wet | >35 MPa | 0.5 | 93309 | 98341 | 102436 | 105700 | 108232 | 110130 | 111482 | 112366 | 112852 | 113002 |

*Number of years to reach full recarbonation of 1 $m^3$ of concrete accounting for overlapping penetration*

# Appendix C

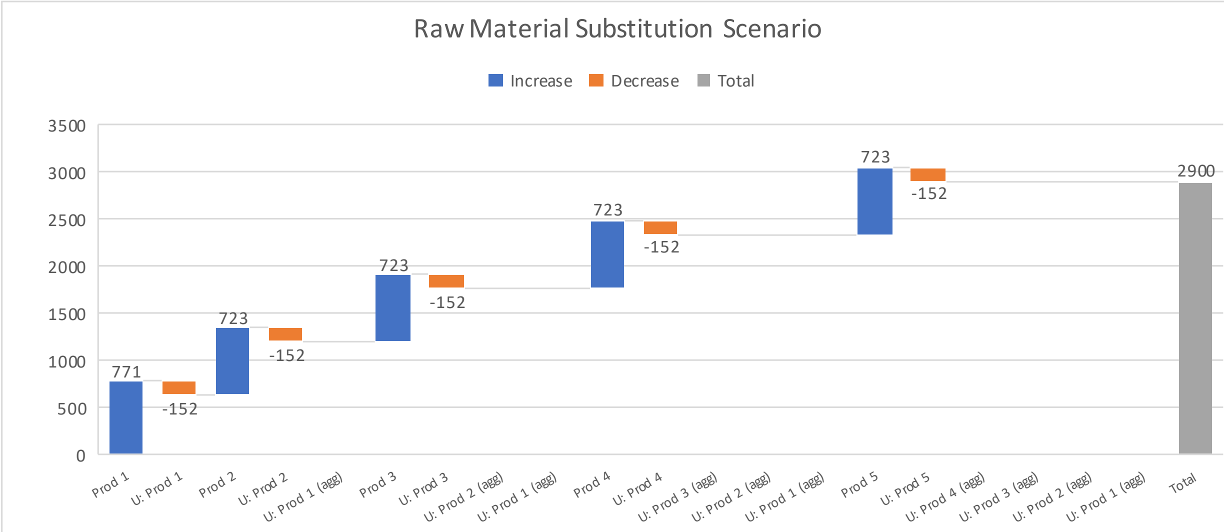
## Model Outputs (Chapter 5 Scenario)

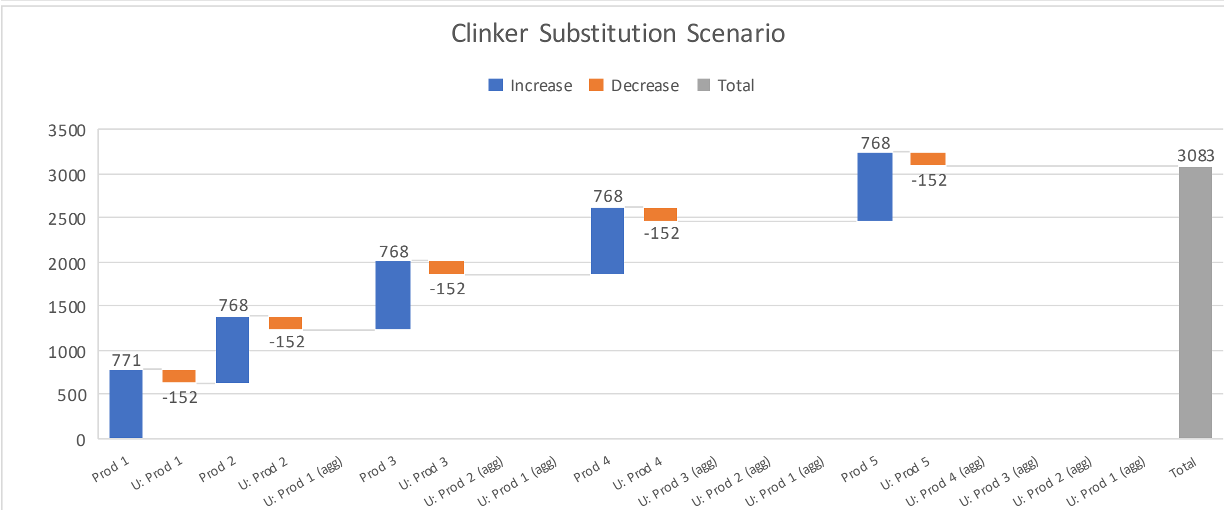
| *Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*<br>*Jurisdiction: Canada; Service Life: 20 years* | **Primary**<br>**Sheltered** | **Secondary**<br>**Exposed** | **Strength**<br>**<15 MPa** |
|---|---|---|---|
| **Substituion Type** | **Raw Material** | **Clinker** | **Aggregates** |
| 1st Production | 771 | 771 | 771 |
| CO2 Uptake Year 0 to 20 | -152 | -152 | -152 |
| 2nd Production | 723 | 768 | 771 |
| CO2 Uptake for Year 21 to 40 (2nd Production) | -152 | -152 | -152 |
| CO2 Uptake for Year 21 to 40 (1st Production Aggregates) | | | -302 |
| 3rd Production | 723 | 768 | 771 |
| CO2 Uptake for Year 41 to 60 (3rd Production) | -152 | -152 | -152 |
| CO2 Uptake for Year 41 to 60 (2nd Production Aggregates) | | | -302 |
| CO2 Uptake for Year 41 to 60 (1st Production Aggregates) | | | 0 |
| 4th Production | 723 | 768 | 771 |
| CO2 Uptake for Year 61 to 80 (4th Production) | -152 | -152 | -152 |
| CO2 Uptake for Year 61 to 80 (3rd Production Aggregates) | | | -302 |
| CO2 Uptake for Year 61 to 80 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 61 to 80 (1st Production Aggregates) | | | 0 |
| 5th Production | 723 | 768 | 771 |
| CO2 Uptake for Year 81 to 100 (4th Production) | -152 | -152 | -152 |
| CO2 Uptake for Year 81 to 100 (4th Production Aggregates) | | | -302 |
| CO2 Uptake for Year 81 to 100 (3rd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (1st Production Aggregates) | | | 0 |
| Total Additive CO2 after 100 years | 2900 | 3083 | 1886 |

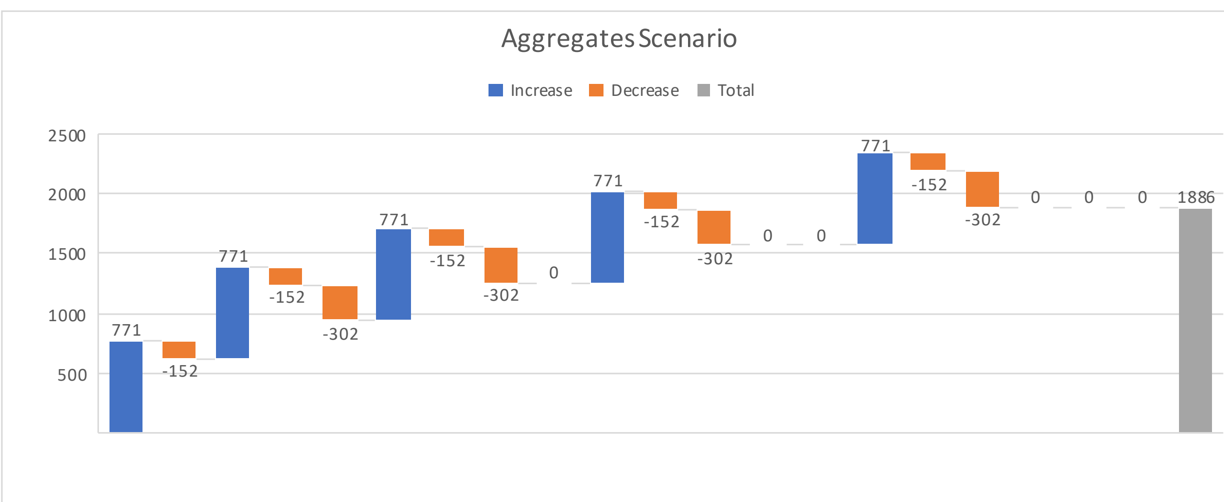
| | | | |
|---|---|---|---|
| Additive CO2 After 20 years | 618.54 | 618.54 | 618.54 |
| Additive CO2 After 40 years | 1,188.87 | 1,234.74 | 937.40 |
| Additive CO2 After 60 years | 1,759.20 | 1,850.94 | 1,256.27 |
| Additive CO2 After 80 years | 2,329.53 | 2,467.14 | 1,575.13 |
| Additive CO2 After 100 years | 2,899.86 | 3,083.34 | 1,894.00 |

*Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*
*Jurisdiction: Canada; Service Life: 20 years*

| | | |
|---|---|---|
| **Primary** | **Secondary** | **Strength** |
| **Sheltered** | **Exposed** | **<15 MPa** |



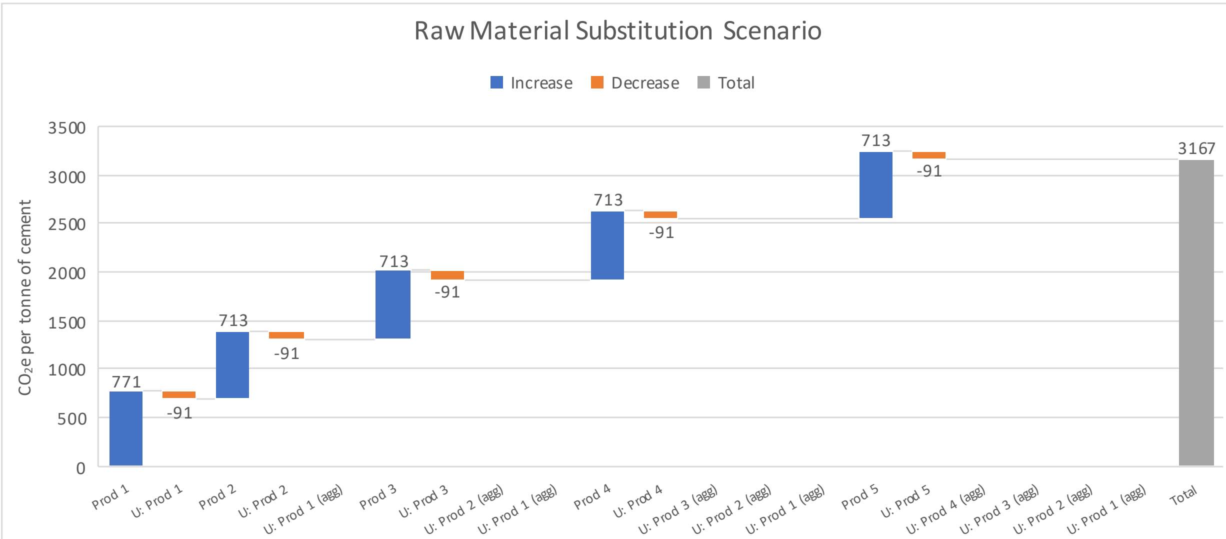



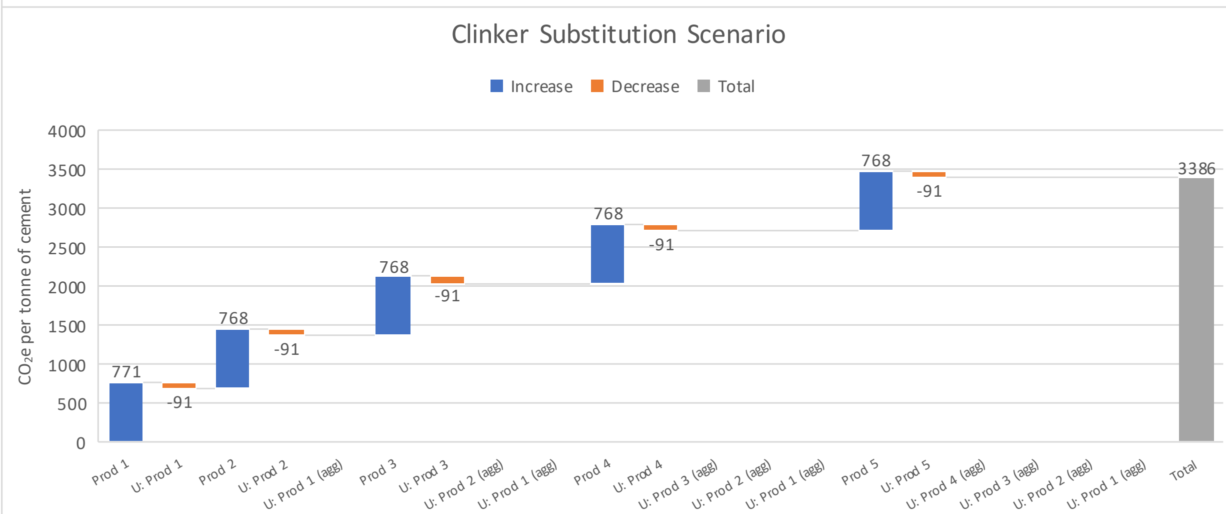
| *Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm Jurisdiction: Canada; Service Life: 20 years* | **Primary**<br>**Sheltered** | **Secondary**<br>**Exposed** | **Strength**<br>**15-20 MPa** |
|---|---|---|---|
| **Substituion Type** | **Raw Material** | **Clinker** | **Aggregates** |
| 1st Production | 771 | 771 | 771 |
| CO2 Uptake Year 0 to 20 | -91 | -91 | -91 |
| 2nd Production | 713 | 768 | 771 |
| CO2 Uptake for Year 21 to 40 (2nd Production) | -91 | -91 | -91 |
| CO2 Uptake for Year 21 to 40 (1st Production Aggregates) | | | -363 |
| 3rd Production | 713 | 768 | 771 |
| CO2 Uptake for Year 41 to 60 (3rd Production) | -91 | -91 | -91 |
| CO2 Uptake for Year 41 to 60 (2nd Production Aggregates) | | | -363 |
| CO2 Uptake for Year 41 to 60 (1st Production Aggregates) | | | 0 |
| 4th Production | 713 | 768 | 771 |
| CO2 Uptake for Year 61 to 80 (4th Production) | -91 | -91 | -91 |
| CO2 Uptake for Year 61 to 80 (3rd Production Aggregates) | | | -363 |
| CO2 Uptake for Year 61 to 80 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 61 to 80 (1st Production Aggregates) | | | 0 |
| 5th Production | 713 | 768 | 771 |
| CO2 Uptake for Year 81 to 100 (4th Production) | -91 | -91 | -91 |
| CO2 Uptake for Year 81 to 100 (4th Production Aggregates) | | | -363 |
| CO2 Uptake for Year 81 to 100 (3rd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (1st Production Aggregates) | | | 0 |
| Total Additive CO2 after 100 years | 3167 | 3386 | 1947 |

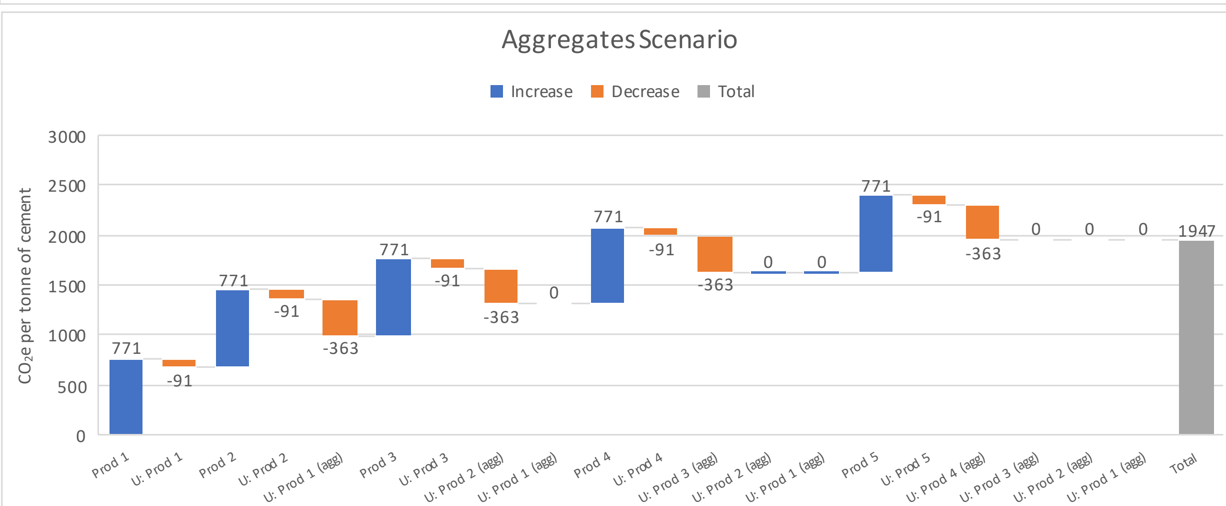
| | | | |
|---|---|---|---|
| Additive CO2 After 20 years | 679.45 | 679.45 | 679.45 |
| Additive CO2 After 40 years | 1,301.38 | 1,356.04 | 998.31 |
| Additive CO2 After 60 years | 1,923.32 | 2,032.64 | 1,317.18 |
| Additive CO2 After 80 years | 2,545.26 | 2,709.24 | 1,636.04 |
| Additive CO2 After 100 years | 3,167.19 | 3,385.84 | 1,954.91 |

*Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*
*Jurisdiction: Canada; Service Life: 20 years*

| Primary | Secondary | Strength |
|---|---|---|
| Sheltered | Exposed | 15-20 MPa |



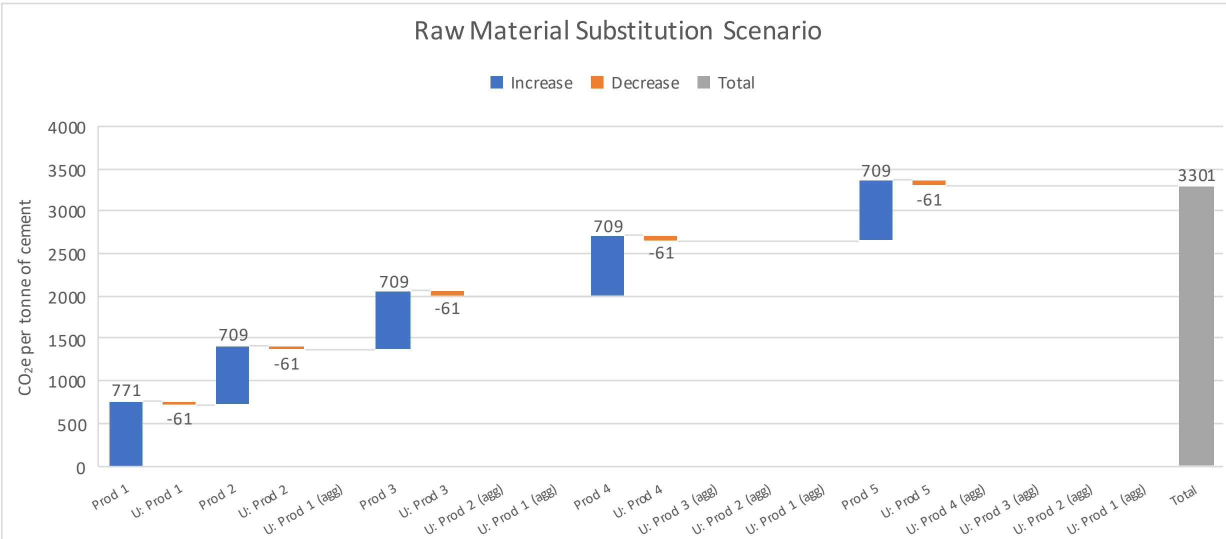



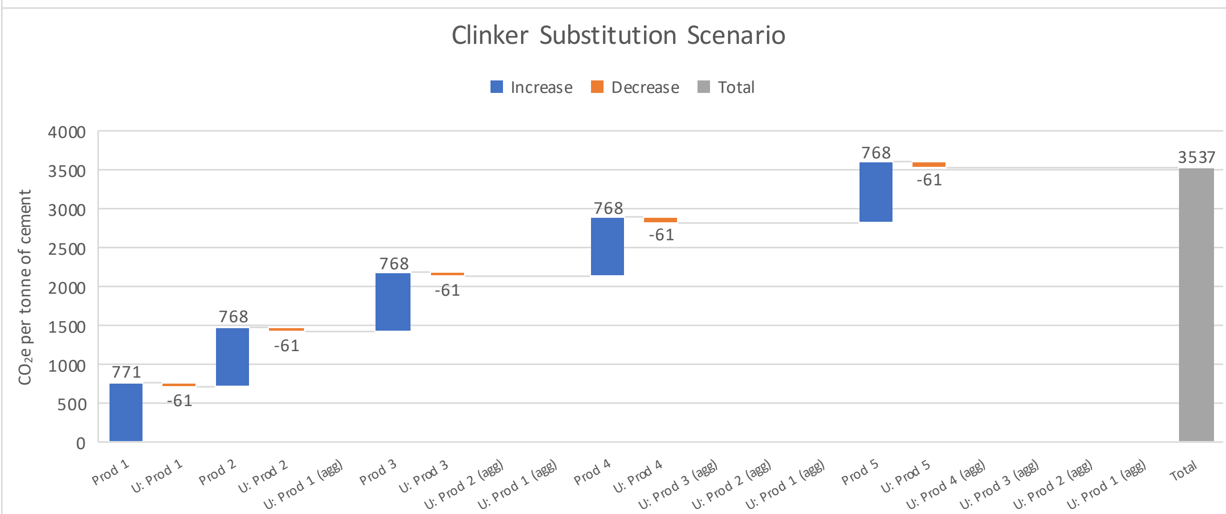
| *Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*<br>*Jurisdiction: Canada; Service Life: 20 years* | **Primary**<br>**Sheltered** | **Secondary**<br>**Exposed** | **Strength**<br>**25-30 MPa** |
|---|---|---|---|
| **Substituion Type** | **Raw Material** | **Clinker** | **Aggregates** |
| 1st Production | 771 | 771 | 771 |
| CO2 Uptake Year 0 to 20 | -61 | -61 | -61 |
| 2nd Production | 709 | 768 | 771 |
| CO2 Uptake for Year 21 to 40 (2nd Production) | -61 | -61 | -61 |
| CO2 Uptake for Year 21 to 40 (1st Production Aggregates) | | | -393 |
| 3rd Production | 709 | 768 | 771 |
| CO2 Uptake for Year 41 to 60 (3rd Production) | -61 | -61 | -61 |
| CO2 Uptake for Year 41 to 60 (2nd Production Aggregates) | | | -393 |
| CO2 Uptake for Year 41 to 60 (1st Production Aggregates) | | | 0 |
| 4th Production | 709 | 768 | 771 |
| CO2 Uptake for Year 61 to 80 (4th Production) | -61 | -61 | -61 |
| CO2 Uptake for Year 61 to 80 (3rd Production Aggregates) | | | -393 |
| CO2 Uptake for Year 61 to 80 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 61 to 80 (1st Production Aggregates) | | | 0 |
| 5th Production | 709 | 768 | 771 |
| CO2 Uptake for Year 81 to 100 (4th Production) | -61 | -61 | -61 |
| CO2 Uptake for Year 81 to 100 (4th Production Aggregates) | | | -393 |
| CO2 Uptake for Year 81 to 100 (3rd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (1st Production Aggregates) | | | 0 |
| Total Additive CO2 after 100 years | 3301 | 3537 | 1977 |

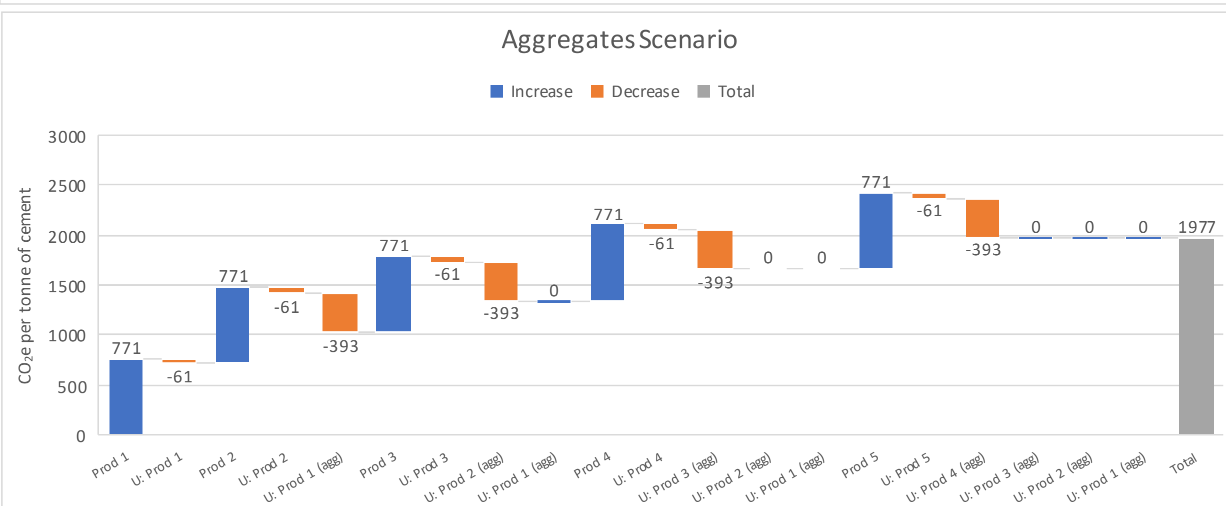
| | | | |
|---|---|---|---|
| Additive CO2 After 20 years | 709.90 | 709.90 | 709.90 |
| Additive CO2 After 40 years | 1,357.69 | 1,416.69 | 1,028.77 |
| Additive CO2 After 60 years | 2,005.48 | 2,123.48 | 1,347.63 |
| Additive CO2 After 80 years | 2,653.28 | 2,830.27 | 1,666.50 |
| Additive CO2 After 100 years | 3,301.07 | 3,537.06 | 1,985.36 |

*Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*
*Jurisdiction: Canada; Service Life: 20 years*

| Primary | Secondary | Strength |
|---|---|---|
| Sheltered | Exposed | 25-30 MPa |



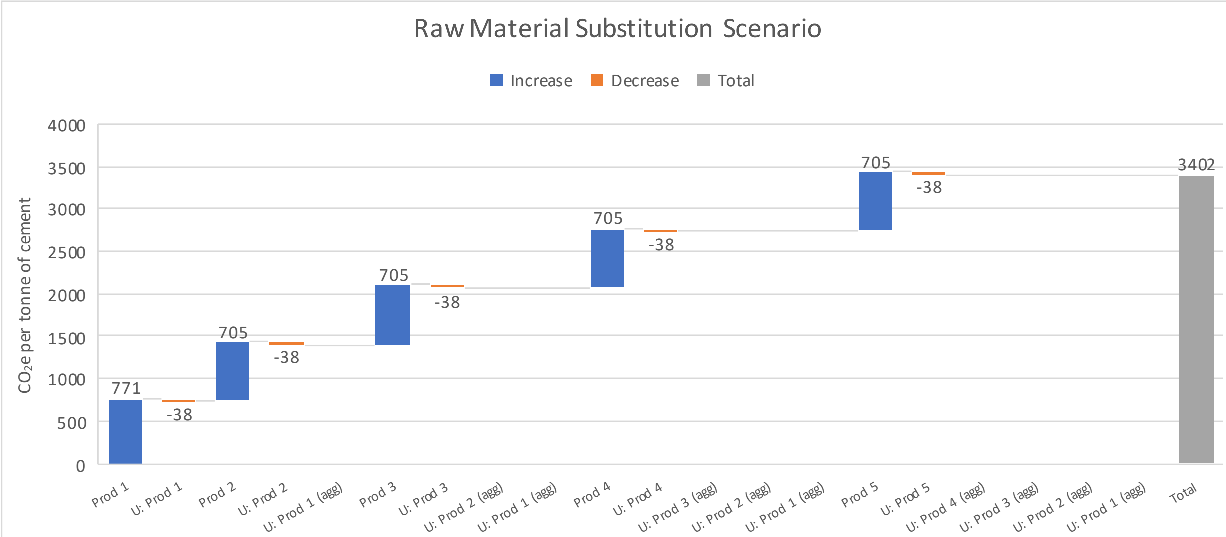



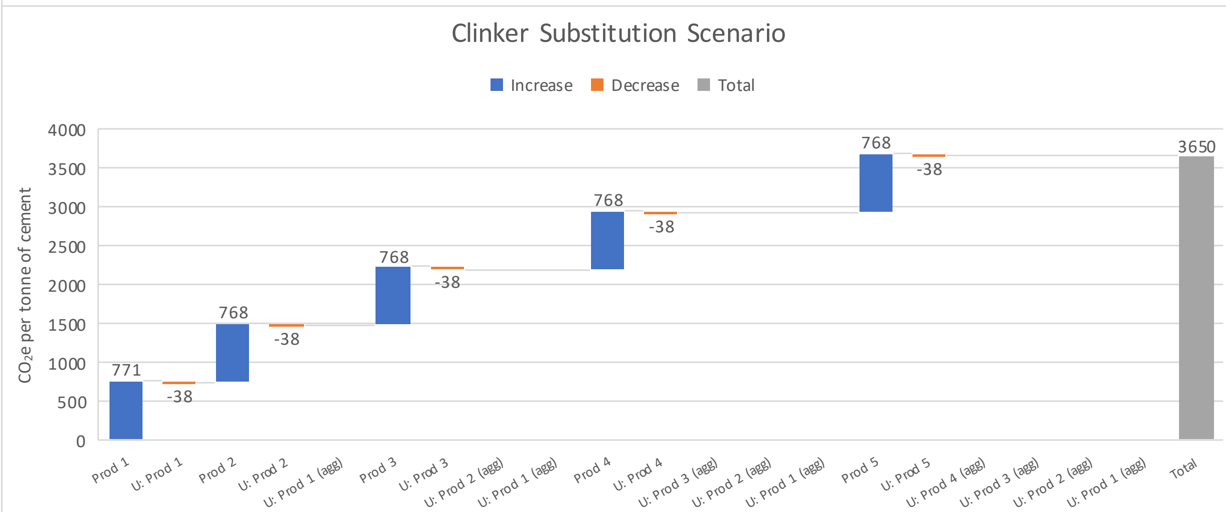
| *Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm<br>Jurisdiction: Canada; Service Life: 20 years* | **Primary**<br>**Sheltered** | **Secondary**<br>**Exposed** | **Strength**<br>**> 35 MPa** |
|---|---|---|---|
| **Substituion Type** | **Raw Material** | **Clinker** | **Aggregates** |
| 1st Production | 771 | 771 | 771 |
| CO2 Uptake Year 0 to 20 | -38 | -38 | -38 |
| 2nd Production | 705 | 768 | 771 |
| CO2 Uptake for Year 21 to 40 (2nd Production) | -38 | -38 | -38 |
| CO2 Uptake for Year 21 to 40 (1st Production Aggregates) | | | -399 |
| 3rd Production | 705 | 768 | 771 |
| CO2 Uptake for Year 41 to 60 (3rd Production) | -38 | -38 | -38 |
| CO2 Uptake for Year 41 to 60 (2nd Production Aggregates) | | | -399 |
| CO2 Uptake for Year 41 to 60 (1st Production Aggregates) | | | -17 |
| 4th Production | 705 | 768 | 771 |
| CO2 Uptake for Year 61 to 80 (4th Production) | -38 | -38 | -38 |
| CO2 Uptake for Year 61 to 80 (3rd Production Aggregates) | | | -399 |
| CO2 Uptake for Year 61 to 80 (2nd Production Aggregates) | | | -17 |
| CO2 Uptake for Year 61 to 80 (1st Production Aggregates) | | | 0 |
| 5th Production | 705 | 768 | 771 |
| CO2 Uptake for Year 81 to 100 (4th Production) | -38 | -38 | -38 |
| CO2 Uptake for Year 81 to 100 (4th Production Aggregates) | | | -399 |
| CO2 Uptake for Year 81 to 100 (3rd Production Aggregates) | | | -17 |
| CO2 Uptake for Year 81 to 100 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (1st Production Aggregates) | | | 0 |
| Total Additive CO2 after 100 years | 3402 | 3650 | 2017 |

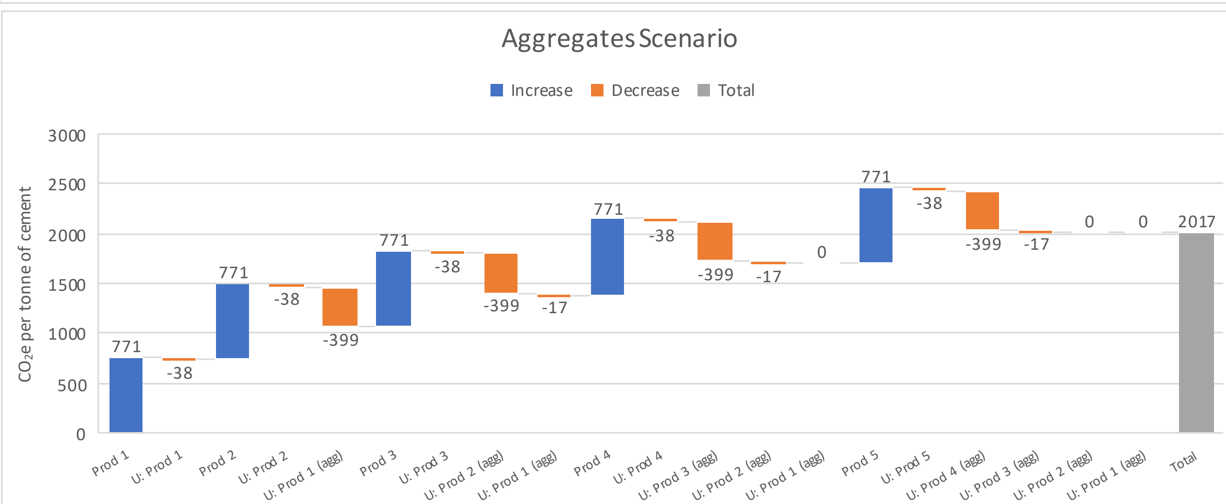
| | | | |
|---|---|---|---|
| Additive CO2 After 20 years | 732.74 | 732.74 | 732.74 |
| Additive CO2 After 40 years | 1,399.95 | 1,462.17 | 1,068.57 |
| Additive CO2 After 60 years | 2,067.15 | 2,191.61 | 1,387.44 |
| Additive CO2 After 80 years | 2,734.36 | 2,921.04 | 1,706.30 |
| Additive CO2 After 100 years | 3,401.56 | 3,650.47 | 2,025.17 |

*Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*
*Jurisdiction: Canada; Service Life: 20 years*

| Primary | Secondary | Strength |
|---|---|---|
| Sheltered | Exposed | > 35 MPa |



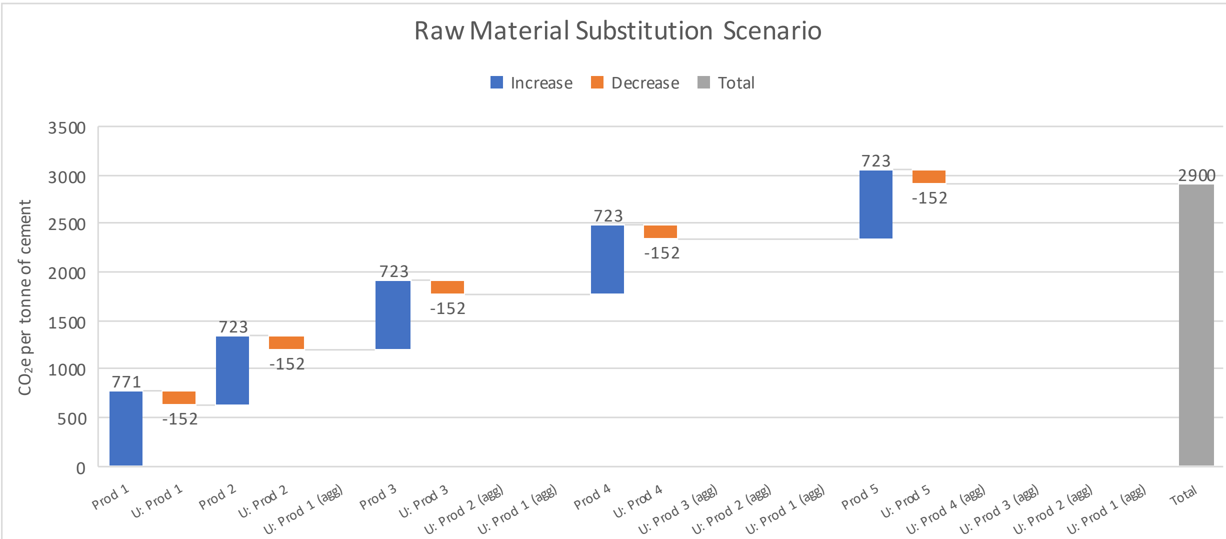



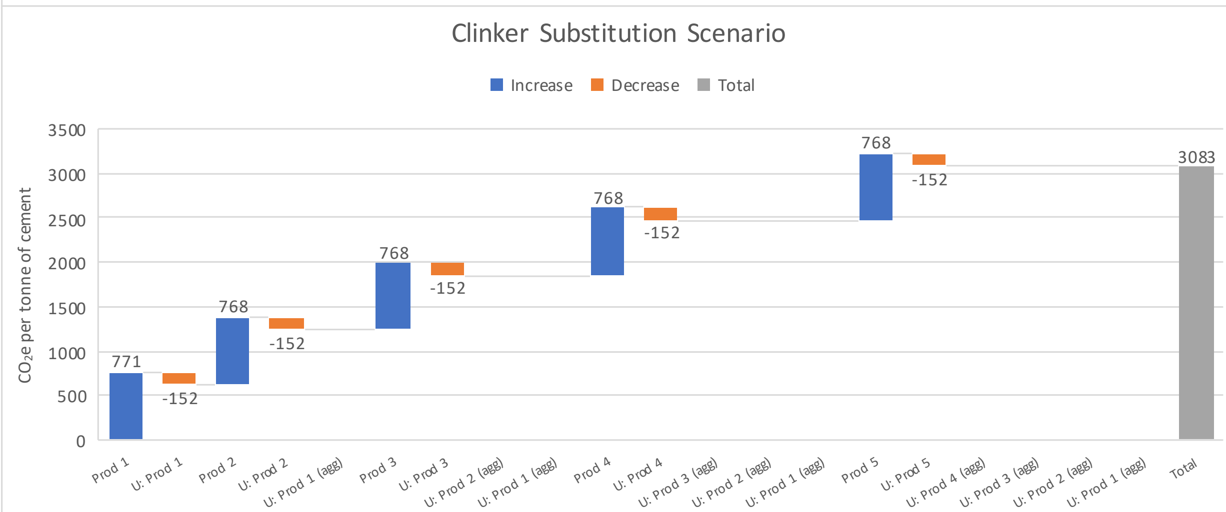
| *Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*<br>*Jurisdiction: Canada; Service Life: 20 years* | **Primary**<br>**Sheltered** | **Secondary**<br>**Buried** | **Strength**<br>**<15 MPa** |
|---|---|---|---|
| **Substituion Type** | **Raw Material** | **Clinker** | **Aggregates** |
| 1st Production | 771 | 771 | 771 |
| CO2 Uptake Year 0 to 20 | -152 | -152 | -152 |
| 2nd Production | 723 | 768 | 771 |
| CO2 Uptake for Year 21 to 40 (2nd Production) | -152 | -152 | -152 |
| CO2 Uptake for Year 21 to 40 (1st Production Aggregates) | | | -302 |
| 3rd Production | 723 | 768 | 771 |
| CO2 Uptake for Year 41 to 60 (3rd Production) | -152 | -152 | -152 |
| CO2 Uptake for Year 41 to 60 (2nd Production Aggregates) | | | -302 |
| CO2 Uptake for Year 41 to 60 (1st Production Aggregates) | | | 0 |
| 4th Production | 723 | 768 | 771 |
| CO2 Uptake for Year 61 to 80 (4th Production) | -152 | -152 | -152 |
| CO2 Uptake for Year 61 to 80 (3rd Production Aggregates) | | | -302 |
| CO2 Uptake for Year 61 to 80 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 61 to 80 (1st Production Aggregates) | | | 0 |
| 5th Production | 723 | 768 | 771 |
| CO2 Uptake for Year 81 to 100 (4th Production) | -152 | -152 | -152 |
| CO2 Uptake for Year 81 to 100 (4th Production Aggregates) | | | -302 |
| CO2 Uptake for Year 81 to 100 (3rd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (1st Production Aggregates) | | | 0 |
| Total Additive CO2 after 100 years | 2900 | 3083 | 1886 |

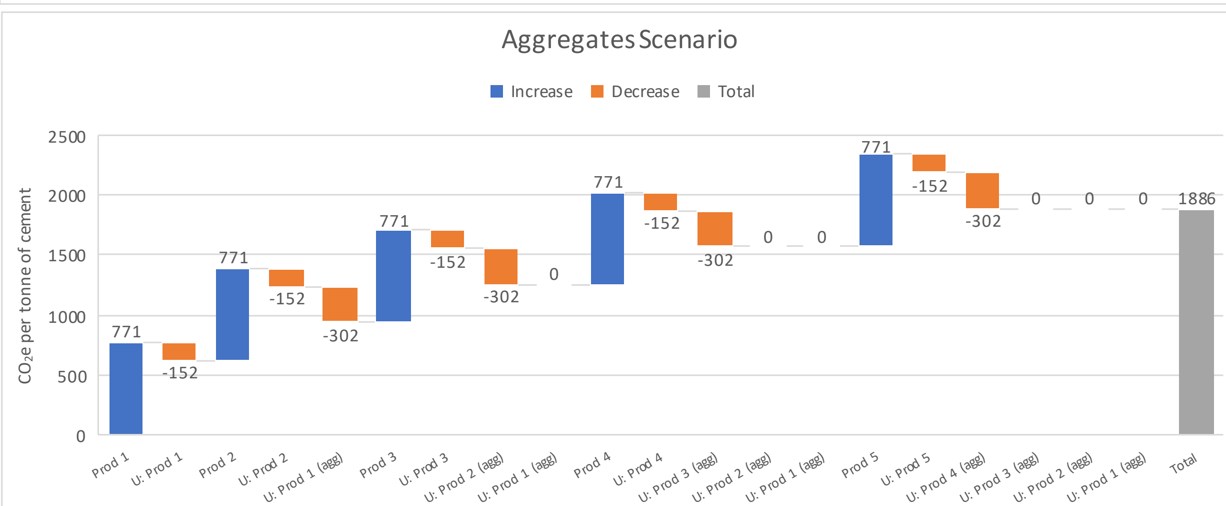
| | | | |
|---|---|---|---|
| Additive CO2 After 20 years | 618.54 | 618.54 | 618.54 |
| Additive CO2 After 40 years | 1,188.87 | 1,234.74 | 937.40 |
| Additive CO2 After 60 years | 1,759.20 | 1,850.94 | 1,256.27 |
| Additive CO2 After 80 years | 2,329.53 | 2,467.14 | 1,575.13 |
| Additive CO2 After 100 years | 2,899.86 | 3,083.34 | 1,894.00 |

*Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*
*Jurisdiction: Canada; Service Life: 20 years*

| **Primary** | **Secondary** | **Strength** |
|---|---|---|
| **Sheltered** | **Buried** | **<15 MPa** |



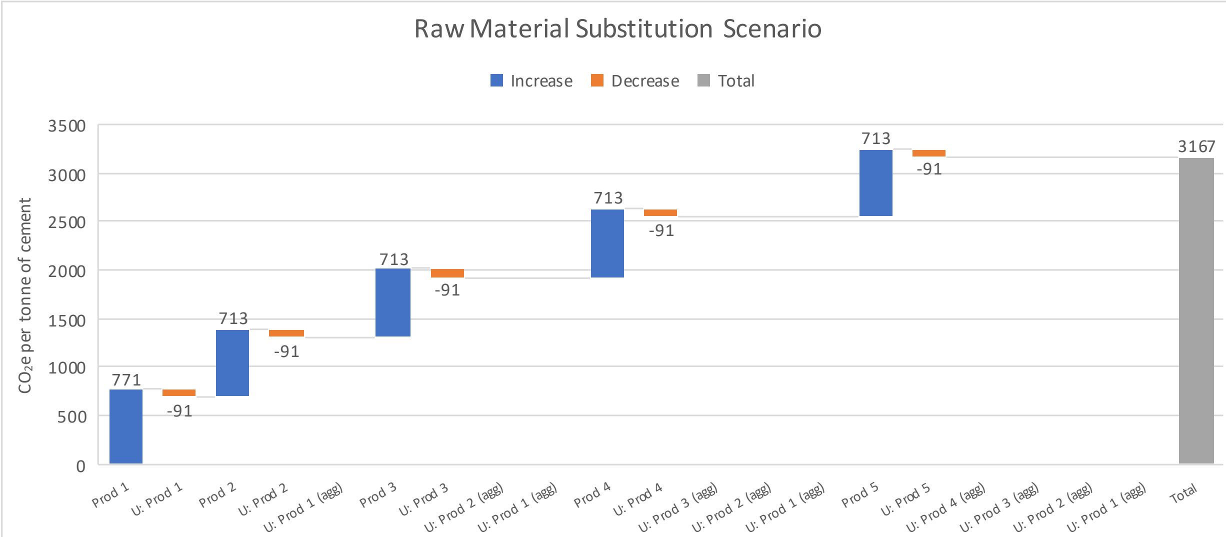



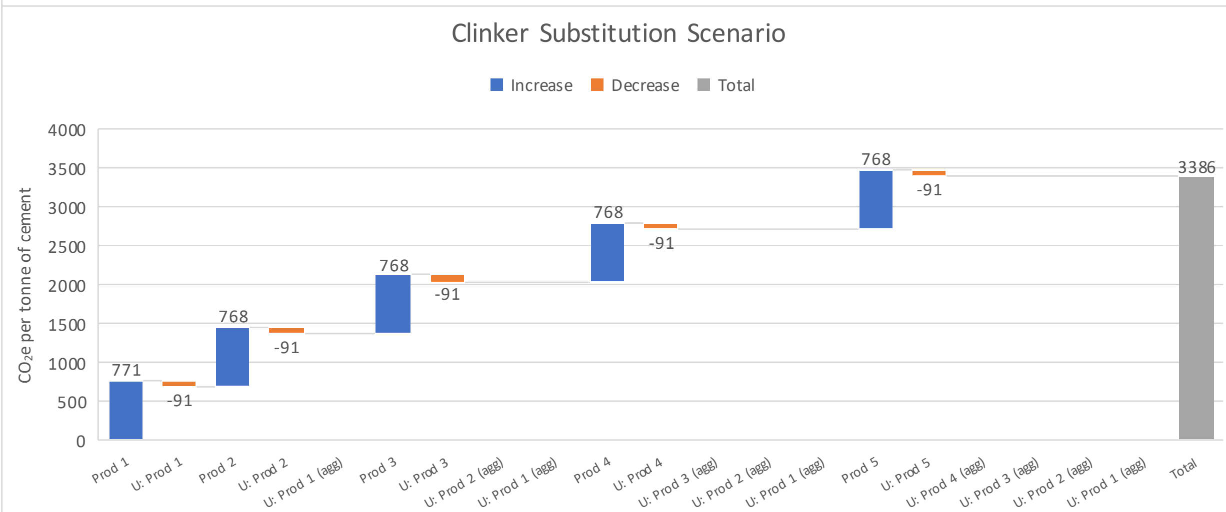
| *Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm<br>Jurisdiction: Canada; Service Life: 20 years* | **Primary**<br>**Sheltered** | **Secondary**<br>**Buried** | **Strength**<br>**15-20 MPa** |
|---|---|---|---|
| **Substituion Type** | **Raw Material** | **Clinker** | **Aggregates** |
| 1st Production | 771 | 771 | 771 |
| CO2 Uptake Year 0 to 20 | -91 | -91 | -91 |
| 2nd Production | 713 | 768 | 771 |
| CO2 Uptake for Year 21 to 40 (2nd Production) | -91 | -91 | -91 |
| CO2 Uptake for Year 21 to 40 (1st Production Aggregates) | | | -363 |
| 3rd Production | 713 | 768 | 771 |
| CO2 Uptake for Year 41 to 60 (3rd Production) | -91 | -91 | -91 |
| CO2 Uptake for Year 41 to 60 (2nd Production Aggregates) | | | -363 |
| CO2 Uptake for Year 41 to 60 (1st Production Aggregates) | | | 0 |
| 4th Production | 713 | 768 | 771 |
| CO2 Uptake for Year 61 to 80 (4th Production) | -91 | -91 | -91 |
| CO2 Uptake for Year 61 to 80 (3rd Production Aggregates) | | | -363 |
| CO2 Uptake for Year 61 to 80 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 61 to 80 (1st Production Aggregates) | | | 0 |
| 5th Production | 713 | 768 | 771 |
| CO2 Uptake for Year 81 to 100 (4th Production) | -91 | -91 | -91 |
| CO2 Uptake for Year 81 to 100 (4th Production Aggregates) | | | -363 |
| CO2 Uptake for Year 81 to 100 (3rd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (1st Production Aggregates) | | | 0 |
| Total Additive CO2 after 100 years | 3167 | 3386 | 1947 |

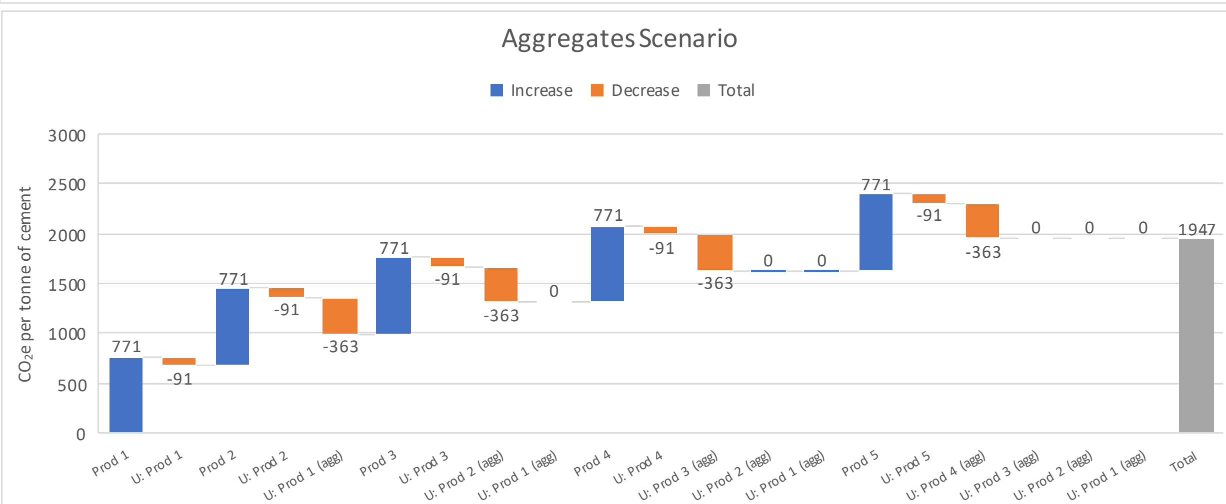
| | | | |
|---|---|---|---|
| Additive CO2 After 20 years | 679.45 | 679.45 | 679.45 |
| Additive CO2 After 40 years | 1,301.38 | 1,356.04 | 998.31 |
| Additive CO2 After 60 years | 1,923.32 | 2,032.64 | 1,317.18 |
| Additive CO2 After 80 years | 2,545.26 | 2,709.24 | 1,636.04 |
| Additive CO2 After 100 years | 3,167.19 | 3,385.84 | 1,954.91 |

*Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*
*Jurisdiction: Canada; Service Life: 20 years*

| Primary | Secondary | Strength |
|---|---|---|
| **Sheltered** | **Buried** | **15-20 MPa** |



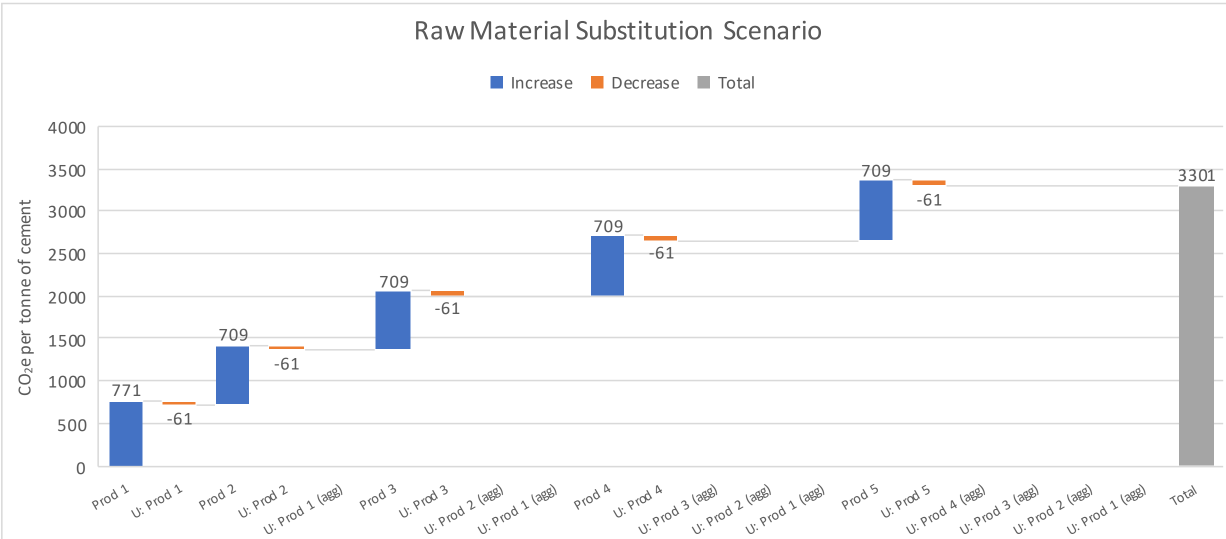



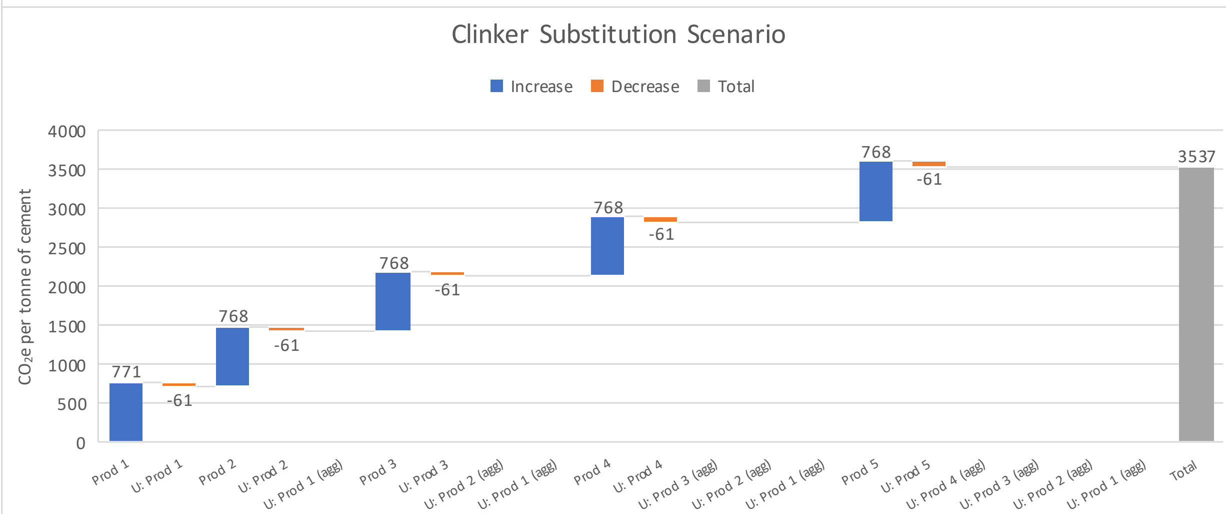
| *Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*<br>*Jurisdiction: Canada; Service Life: 20 years* | **Primary**<br>**Sheltered** | **Secondary**<br>**Buried** | **Strength**<br>**25-30 MPa** |
|---|---|---|---|
| **Substituion Type** | **Raw Material** | **Clinker** | **Aggregates** |
| 1st Production | 771 | 771 | 771 |
| CO2 Uptake Year 0 to 20 | -61 | -61 | -61 |
| 2nd Production | 709 | 768 | 771 |
| CO2 Uptake for Year 21 to 40 (2nd Production) | -61 | -61 | -61 |
| CO2 Uptake for Year 21 to 40 (1st Production Aggregates) | | | -393 |
| 3rd Production | 709 | 768 | 771 |
| CO2 Uptake for Year 41 to 60 (3rd Production) | -61 | -61 | -61 |
| CO2 Uptake for Year 41 to 60 (2nd Production Aggregates) | | | -393 |
| CO2 Uptake for Year 41 to 60 (1st Production Aggregates) | | | 0 |
| 4th Production | 709 | 768 | 771 |
| CO2 Uptake for Year 61 to 80 (4th Production) | -61 | -61 | -61 |
| CO2 Uptake for Year 61 to 80 (3rd Production Aggregates) | | | -393 |
| CO2 Uptake for Year 61 to 80 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 61 to 80 (1st Production Aggregates) | | | 0 |
| 5th Production | 709 | 768 | 771 |
| CO2 Uptake for Year 81 to 100 (4th Production) | -61 | -61 | -61 |
| CO2 Uptake for Year 81 to 100 (4th Production Aggregates) | | | -393 |
| CO2 Uptake for Year 81 to 100 (3rd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (1st Production Aggregates) | | | 0 |
| Total Additive CO2 after 100 years | 3301 | 3537 | 1977 |

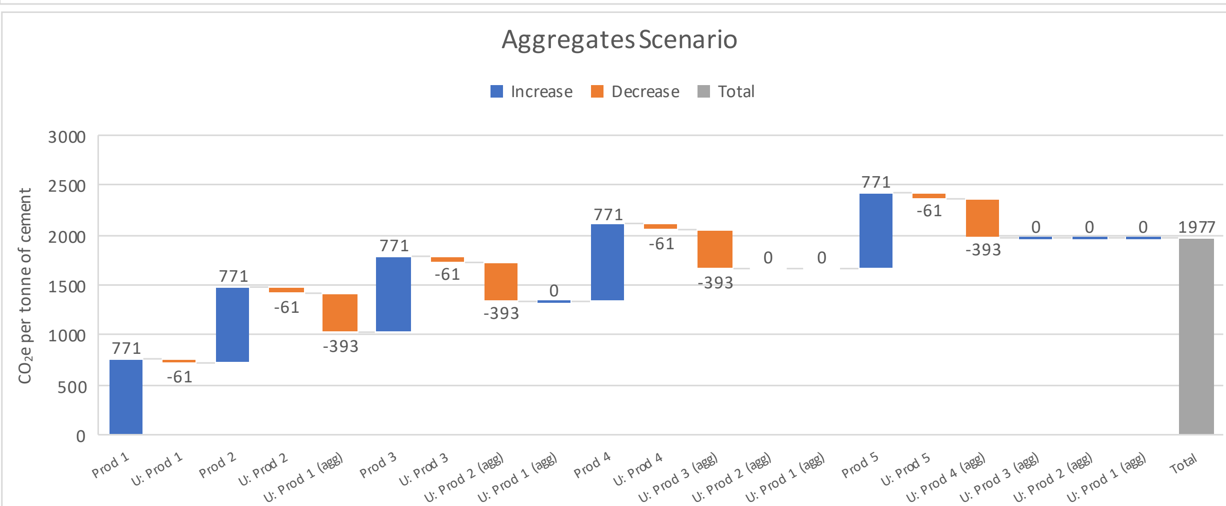
| | | | |
|---|---|---|---|
| Additive CO2 After 20 years | 709.90 | 709.90 | 709.90 |
| Additive CO2 After 40 years | 1,357.69 | 1,416.69 | 1,028.77 |
| Additive CO2 After 60 years | 2,005.48 | 2,123.48 | 1,347.63 |
| Additive CO2 After 80 years | 2,653.28 | 2,830.27 | 1,666.50 |
| Additive CO2 After 100 years | 3,301.07 | 3,537.06 | 1,985.36 |

*Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*
*Jurisdiction: Canada; Service Life: 20 years*

| Primary | Secondary | Strength |
|---|---|---|
| Sheltered | Buried | 25-30 MPa |



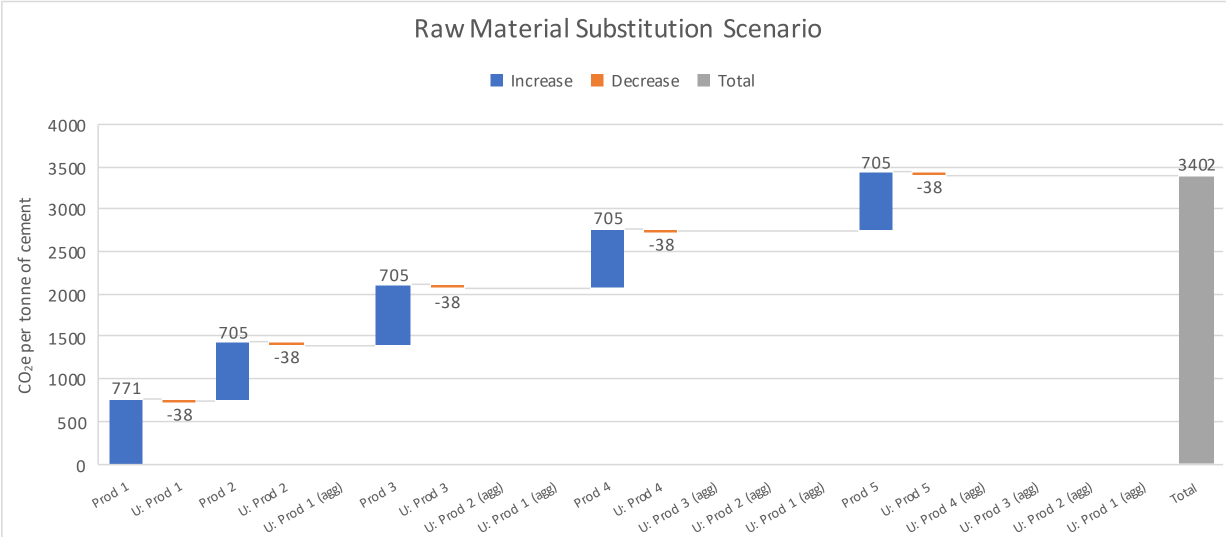



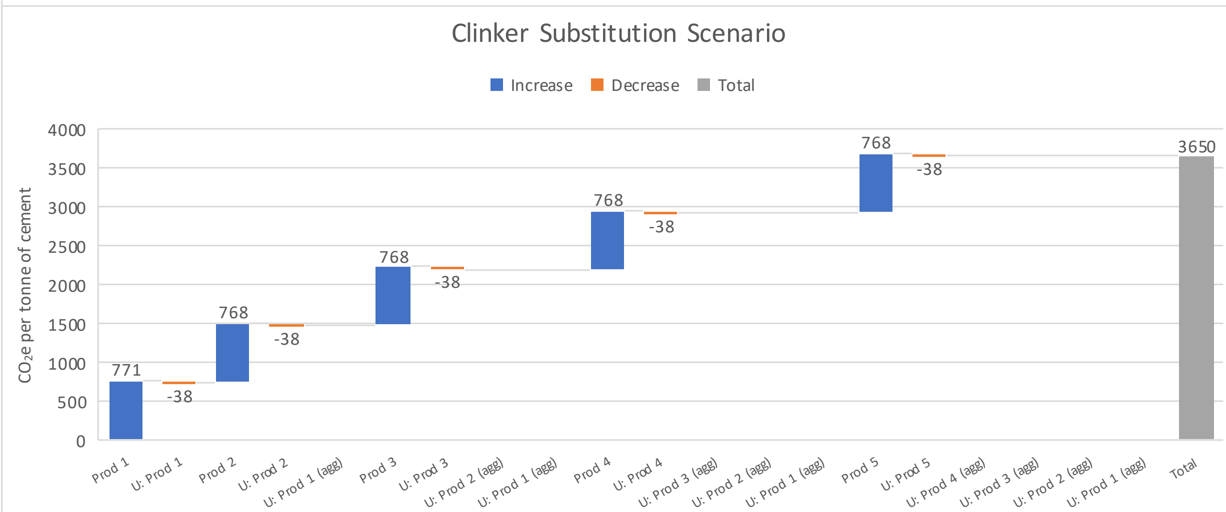
| *Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*<br>*Jurisdiction: Canada; Service Life: 20 years* | **Primary**<br>**Sheltered** | **Secondary**<br>**Buried** | **Strength**<br>**> 35 MPa** |
|---|---|---|---|
| **Substituion Type** | **Raw Material** | **Clinker** | **Aggregates** |
| 1st Production | 771 | 771 | 771 |
| CO2 Uptake Year 0 to 20 | -38 | -38 | -38 |
| 2nd Production | 705 | 768 | 771 |
| CO2 Uptake for Year 21 to 40 (2nd Production) | -38 | -38 | -38 |
| CO2 Uptake for Year 21 to 40 (1st Production Aggregates) | | | -299 |
| 3rd Production | 705 | 768 | 771 |
| CO2 Uptake for Year 41 to 60 (3rd Production) | -38 | -38 | -38 |
| CO2 Uptake for Year 41 to 60 (2nd Production Aggregates) | | | -299 |
| CO2 Uptake for Year 41 to 60 (1st Production Aggregates) | | | -117 |
| 4th Production | 705 | 768 | 771 |
| CO2 Uptake for Year 61 to 80 (4th Production) | -38 | -38 | -38 |
| CO2 Uptake for Year 61 to 80 (3rd Production Aggregates) | | | -299 |
| CO2 Uptake for Year 61 to 80 (2nd Production Aggregates) | | | -117 |
| CO2 Uptake for Year 61 to 80 (1st Production Aggregates) | | | 0 |
| 5th Production | 705 | 768 | 771 |
| CO2 Uptake for Year 81 to 100 (4th Production) | -38 | -38 | -38 |
| CO2 Uptake for Year 81 to 100 (4th Production Aggregates) | | | -299 |
| CO2 Uptake for Year 81 to 100 (3rd Production Aggregates) | | | -117 |
| CO2 Uptake for Year 81 to 100 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (1st Production Aggregates) | | | 0 |
| Total Additive CO2 after 100 years | 3402 | 3650 | 2117 |

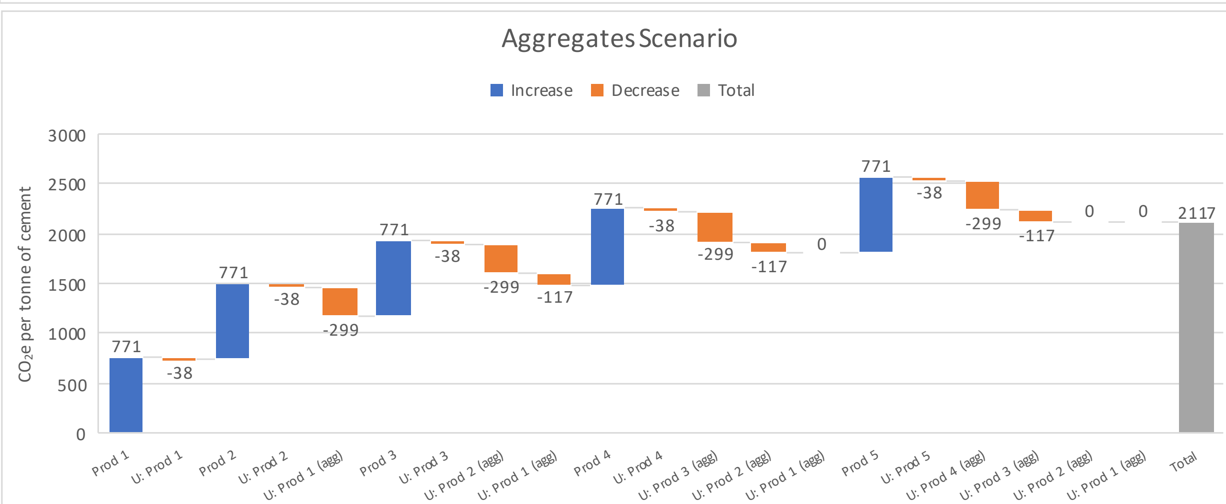
| | | | |
|---|---|---|---|
| Additive CO2 After 20 years | 732.74 | 732.74 | 732.74 |
| Additive CO2 After 40 years | 1,399.95 | 1,462.17 | 1,168.31 |
| Additive CO2 After 60 years | 2,067.15 | 2,191.61 | 1,487.18 |
| Additive CO2 After 80 years | 2,734.36 | 2,921.04 | 1,806.04 |
| Additive CO2 After 100 years | 3,401.56 | 3,650.47 | 2,124.91 |

*Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*
*Jurisdiction: Canada; Service Life: 20 years*

| Primary | Secondary | Strength |
|---|---|---|
| Sheltered | Buried | > 35 MPa |



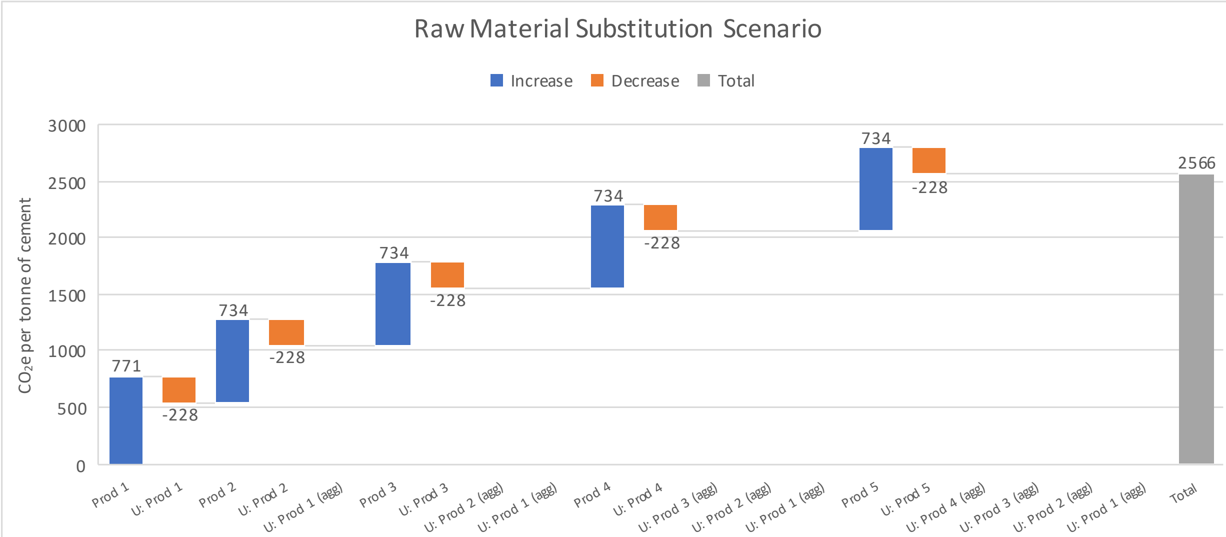



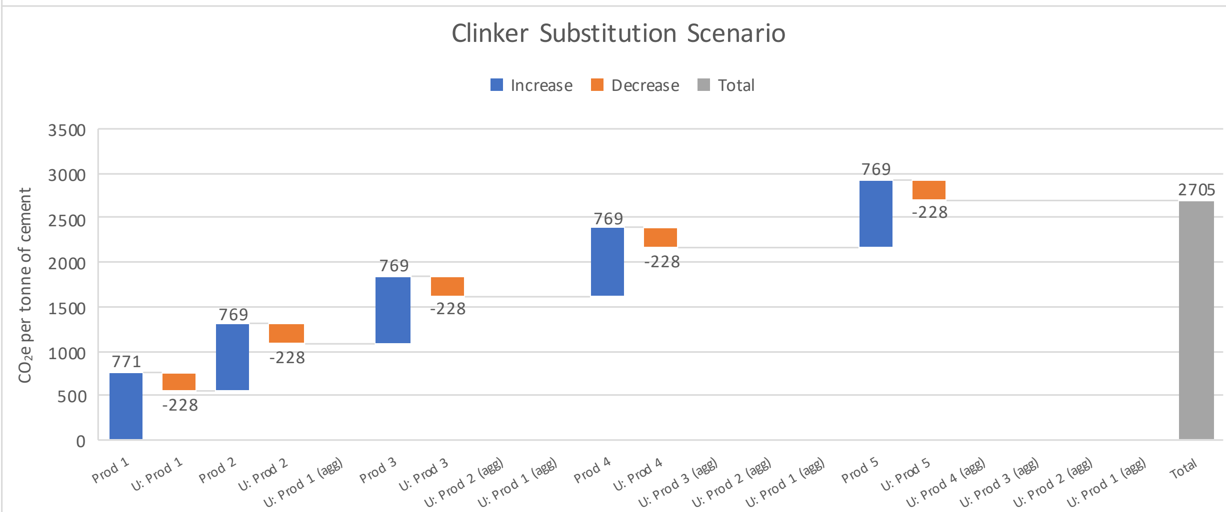
| *Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*<br>*Jurisdiction: Canada; Service Life: 20 years* | **Primary**<br>**Indoors** | **Secondary**<br>**Exposed** | **Strength**<br>**<15 MPa** |
|---|---|---|---|
| **Substituion Type** | **Raw Material** | **Clinker** | **Aggregates** |
| 1st Production | 771 | 771 | 771 |
| CO2 Uptake Year 0 to 20 | -228 | -228 | -228 |
| 2nd Production | 734 | 769 | 771 |
| CO2 Uptake for Year 21 to 40 (2nd Production) | -228 | -228 | -228 |
| CO2 Uptake for Year 21 to 40 (1st Production Aggregates) | | | -226 |
| 3rd Production | 734 | 769 | 771 |
| CO2 Uptake for Year 41 to 60 (3rd Production) | -228 | -228 | -228 |
| CO2 Uptake for Year 41 to 60 (2nd Production Aggregates) | | | -226 |
| CO2 Uptake for Year 41 to 60 (1st Production Aggregates) | | | 0 |
| 4th Production | 734 | 769 | 771 |
| CO2 Uptake for Year 61 to 80 (4th Production) | -228 | -228 | -228 |
| CO2 Uptake for Year 61 to 80 (3rd Production Aggregates) | | | -226 |
| CO2 Uptake for Year 61 to 80 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 61 to 80 (1st Production Aggregates) | | | 0 |
| 5th Production | 734 | 769 | 771 |
| CO2 Uptake for Year 81 to 100 (4th Production) | -228 | -228 | -228 |
| CO2 Uptake for Year 81 to 100 (4th Production Aggregates) | | | -226 |
| CO2 Uptake for Year 81 to 100 (3rd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (1st Production Aggregates) | | | 0 |
| Total Additive CO2 after 100 years | 2566 | 2705 | 1810 |

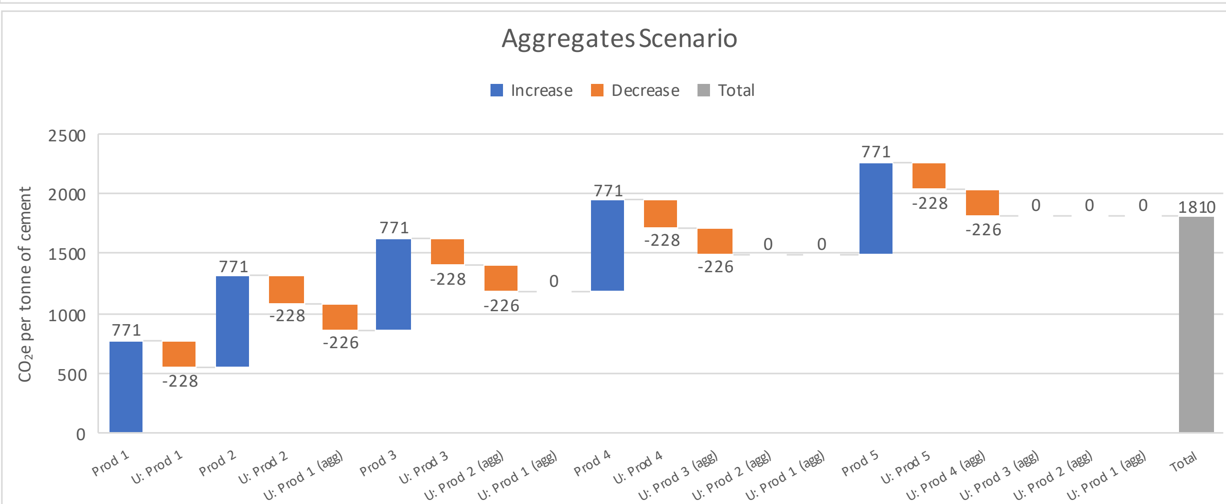
| | | | |
|---|---|---|---|
| Additive CO2 After 20 years | 542.40 | 542.40 | 542.40 |
| Additive CO2 After 40 years | 1,048.42 | 1,083.08 | 861.27 |
| Additive CO2 After 60 years | 1,554.44 | 1,623.77 | 1,180.13 |
| Additive CO2 After 80 years | 2,060.46 | 2,164.45 | 1,499.00 |
| Additive CO2 After 100 years | 2,566.48 | 2,705.13 | 1,817.86 |

*Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*
*Jurisdiction: Canada; Service Life: 20 years*

| Primary | Secondary | Strength |
|---|---|---|
| Indoors | Exposed | <15 MPa |



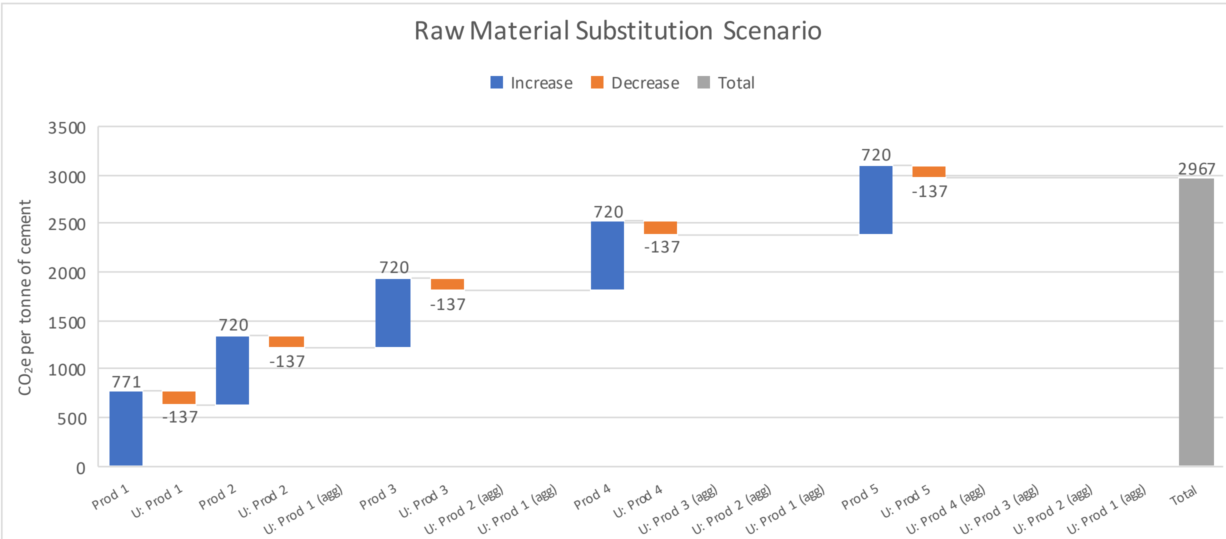



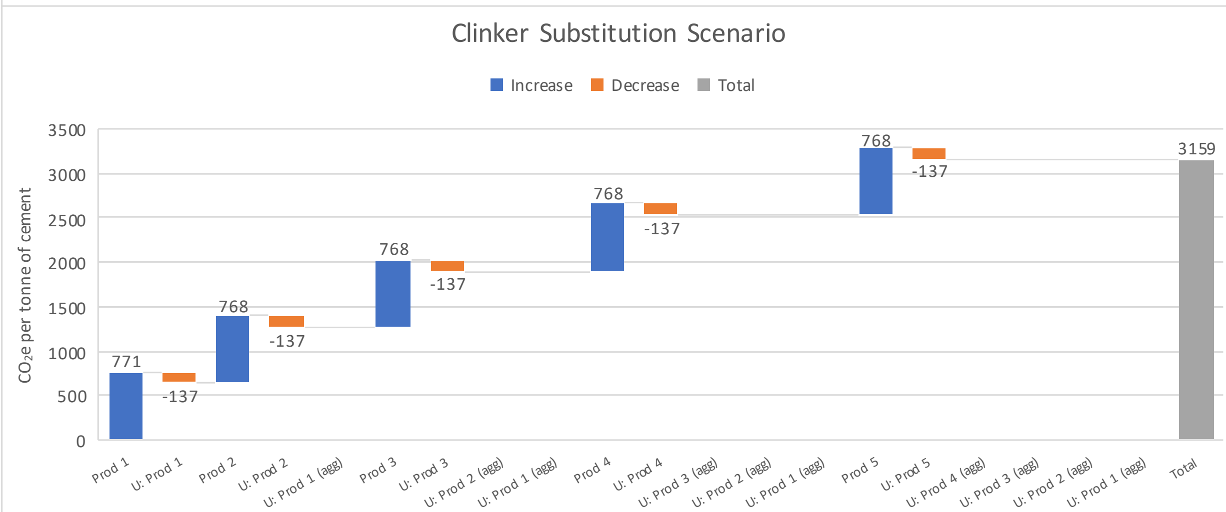
| *Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*<br>*Jurisdiction: Canada; Service Life: 20 years* | **Primary**<br>**Indoors** | **Secondary**<br>**Exposed** | **Strength**<br>**15-20 MPa** |
|---|---|---|---|
| **Substituion Type** | **Raw Material** | **Clinker** | **Aggregates** |
| 1st Production | 771 | 771 | 771 |
| CO2 Uptake Year 0 to 20 | -137 | -137 | -137 |
| 2nd Production | 720 | 768 | 771 |
| CO2 Uptake for Year 21 to 40 (2nd Production) | -137 | -137 | -137 |
| CO2 Uptake for Year 21 to 40 (1st Production Aggregates) | | | -317 |
| 3rd Production | 720 | 768 | 771 |
| CO2 Uptake for Year 41 to 60 (3rd Production) | -137 | -137 | -137 |
| CO2 Uptake for Year 41 to 60 (2nd Production Aggregates) | | | -317 |
| CO2 Uptake for Year 41 to 60 (1st Production Aggregates) | | | 0 |
| 4th Production | 720 | 768 | 771 |
| CO2 Uptake for Year 61 to 80 (4th Production) | -137 | -137 | -137 |
| CO2 Uptake for Year 61 to 80 (3rd Production Aggregates) | | | -317 |
| CO2 Uptake for Year 61 to 80 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 61 to 80 (1st Production Aggregates) | | | 0 |
| 5th Production | 720 | 768 | 771 |
| CO2 Uptake for Year 81 to 100 (4th Production) | -137 | -137 | -137 |
| CO2 Uptake for Year 81 to 100 (4th Production Aggregates) | | | -317 |
| CO2 Uptake for Year 81 to 100 (3rd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (1st Production Aggregates) | | | 0 |
| Total Additive CO2 after 100 years | 2967 | 3159 | 1901 |

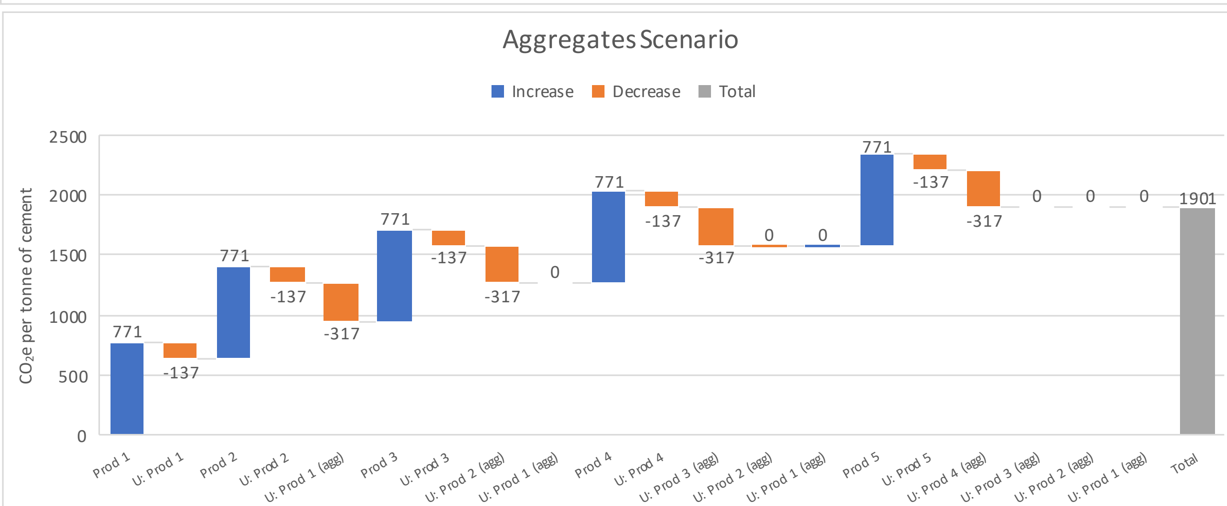
| | | | |
|---|---|---|---|
| Additive CO2 After 20 years | 633.76 | 633.76 | 633.76 |
| Additive CO2 After 40 years | 1,216.98 | 1,265.07 | 952.63 |
| Additive CO2 After 60 years | 1,800.20 | 1,896.37 | 1,271.49 |
| Additive CO2 After 80 years | 2,383.42 | 2,527.67 | 1,590.36 |
| Additive CO2 After 100 years | 2,966.64 | 3,158.97 | 1,909.22 |

*Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*
*Jurisdiction: Canada; Service Life: 20 years*

| Primary | Secondary | Strength |
| --- | --- | --- |
| Indoors | Exposed | 15-20 MPa |



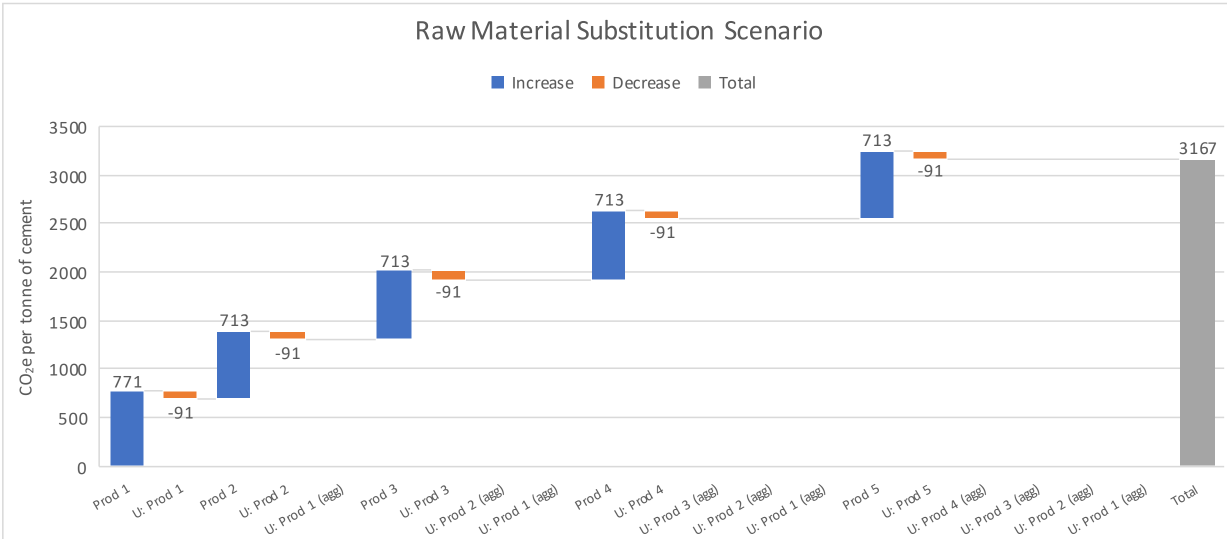



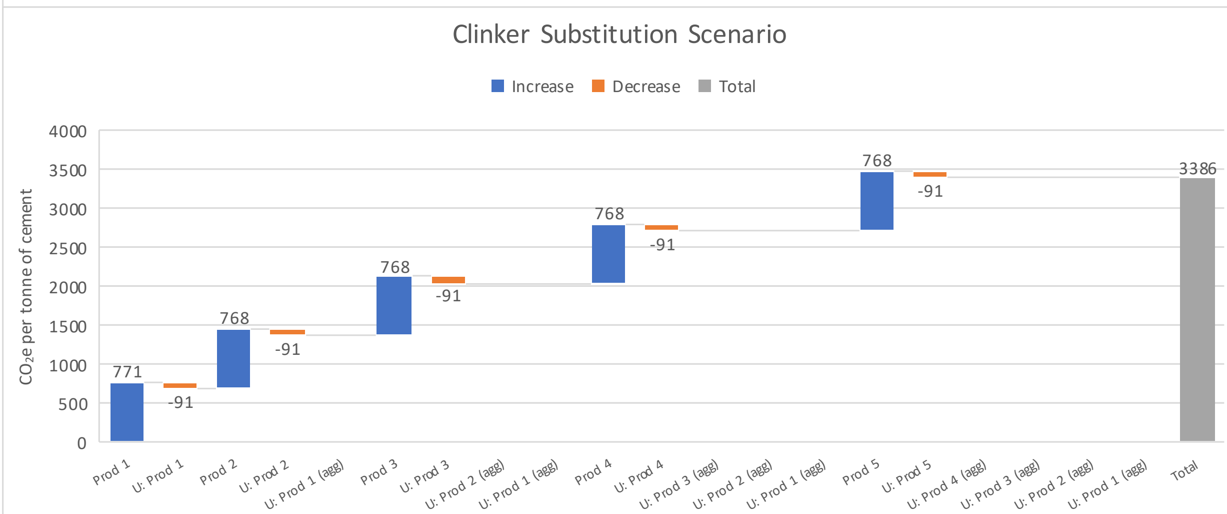
| *Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*<br>*Jurisdiction: Canada; Service Life: 20 years* | **Primary**<br>**Indoors** | **Secondary**<br>**Exposed** | **Strength**<br>**25-30 MPa** |
|---|---|---|---|
| **Substituion Type** | **Raw Material** | **Clinker** | **Aggregates** |
| 1st Production | 771 | 771 | 771 |
| CO2 Uptake Year 0 to 20 | -91 | -91 | -91 |
| 2nd Production | 713 | 768 | 771 |
| CO2 Uptake for Year 21 to 40 (2nd Production) | -91 | -91 | -91 |
| CO2 Uptake for Year 21 to 40 (1st Production Aggregates) | | | -363 |
| 3rd Production | 713 | 768 | 771 |
| CO2 Uptake for Year 41 to 60 (3rd Production) | -91 | -91 | -91 |
| CO2 Uptake for Year 41 to 60 (2nd Production Aggregates) | | | -363 |
| CO2 Uptake for Year 41 to 60 (1st Production Aggregates) | | | 0 |
| 4th Production | 713 | 768 | 771 |
| CO2 Uptake for Year 61 to 80 (4th Production) | -91 | -91 | -91 |
| CO2 Uptake for Year 61 to 80 (3rd Production Aggregates) | | | -363 |
| CO2 Uptake for Year 61 to 80 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 61 to 80 (1st Production Aggregates) | | | 0 |
| 5th Production | 713 | 768 | 771 |
| CO2 Uptake for Year 81 to 100 (4th Production) | -91 | -91 | -91 |
| CO2 Uptake for Year 81 to 100 (4th Production Aggregates) | | | -363 |
| CO2 Uptake for Year 81 to 100 (3rd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (1st Production Aggregates) | | | 0 |
| Total Additive CO2 after 100 years | 3167 | 3386 | 1947 |

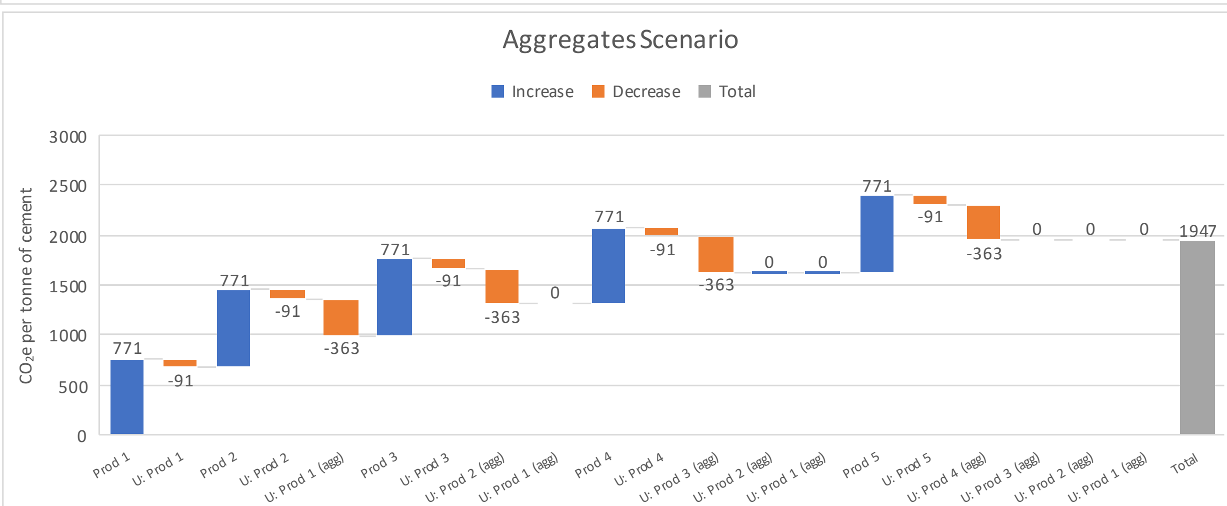
| | | | |
|---|---|---|---|
| Additive CO2 After 20 years | 679.45 | 679.45 | 679.45 |
| Additive CO2 After 40 years | 1,301.38 | 1,356.04 | 998.31 |
| Additive CO2 After 60 years | 1,923.32 | 2,032.64 | 1,317.18 |
| Additive CO2 After 80 years | 2,545.26 | 2,709.24 | 1,636.04 |
| Additive CO2 After 100 years | 3,167.19 | 3,385.84 | 1,954.91 |

*Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*
*Jurisdiction: Canada; Service Life: 20 years*

| **Primary** | **Secondary** | **Strength** |
|---|---|---|
| **Indoors** | **Exposed** | **25-30 MPa** |



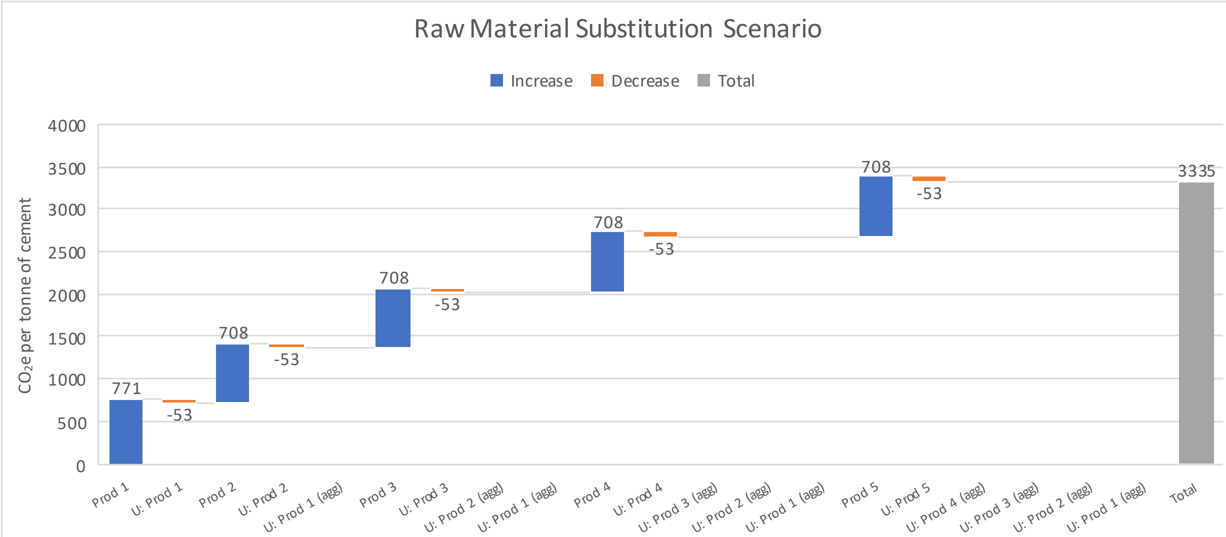



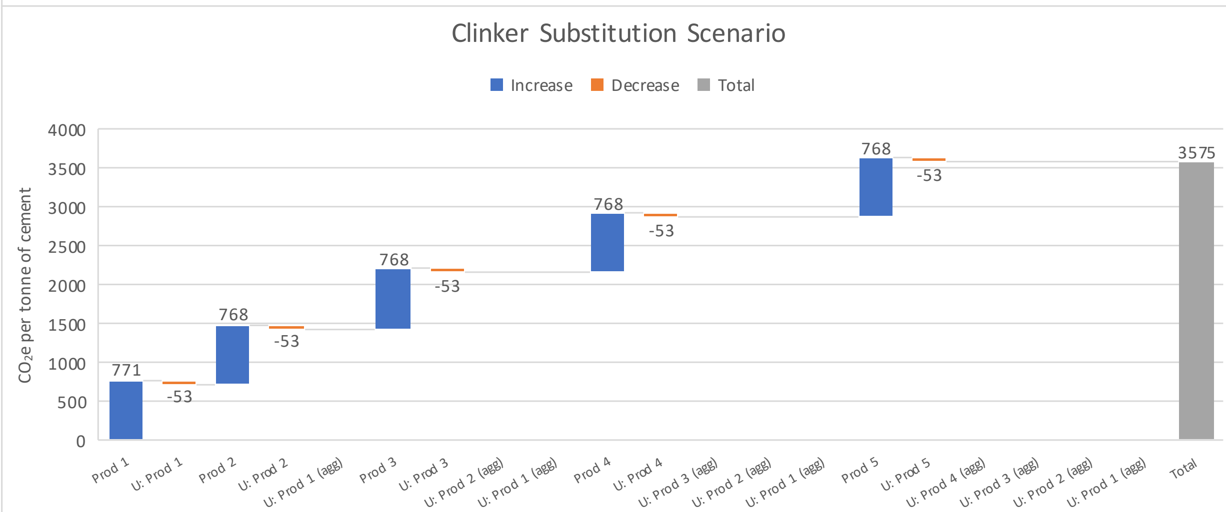
| *Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*<br>*Jurisdiction: Canada; Service Life: 20 years* | **Primary**<br>**Indoors** | **Secondary**<br>**Exposed** | **Strength**<br>**> 35 MPa** |
|---|---|---|---|
| **Substituion Type** | **Raw Material** | **Clinker** | **Aggregates** |
| 1st Production | 771 | 771 | 771 |
| CO2 Uptake Year 0 to 20 | -53 | -53 | -53 |
| 2nd Production | 708 | 768 | 771 |
| CO2 Uptake for Year 21 to 40 (2nd Production) | -53 | -53 | -53 |
| CO2 Uptake for Year 21 to 40 (1st Production Aggregates) | | | -399 |
| 3rd Production | 708 | 768 | 771 |
| CO2 Uptake for Year 41 to 60 (3rd Production) | -53 | -53 | -53 |
| CO2 Uptake for Year 41 to 60 (2nd Production Aggregates) | | | -399 |
| CO2 Uptake for Year 41 to 60 (1st Production Aggregates) | | | -2 |
| 4th Production | 708 | 768 | 771 |
| CO2 Uptake for Year 61 to 80 (4th Production) | -53 | -53 | -53 |
| CO2 Uptake for Year 61 to 80 (3rd Production Aggregates) | | | -399 |
| CO2 Uptake for Year 61 to 80 (2nd Production Aggregates) | | | -2 |
| CO2 Uptake for Year 61 to 80 (1st Production Aggregates) | | | 0 |
| 5th Production | 708 | 768 | 771 |
| CO2 Uptake for Year 81 to 100 (4th Production) | -53 | -53 | -53 |
| CO2 Uptake for Year 81 to 100 (4th Production Aggregates) | | | -399 |
| CO2 Uptake for Year 81 to 100 (3rd Production Aggregates) | | | -2 |
| CO2 Uptake for Year 81 to 100 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (1st Production Aggregates) | | | 0 |
| Total Additive CO2 after 100 years | 3335 | 3575 | 1987 |

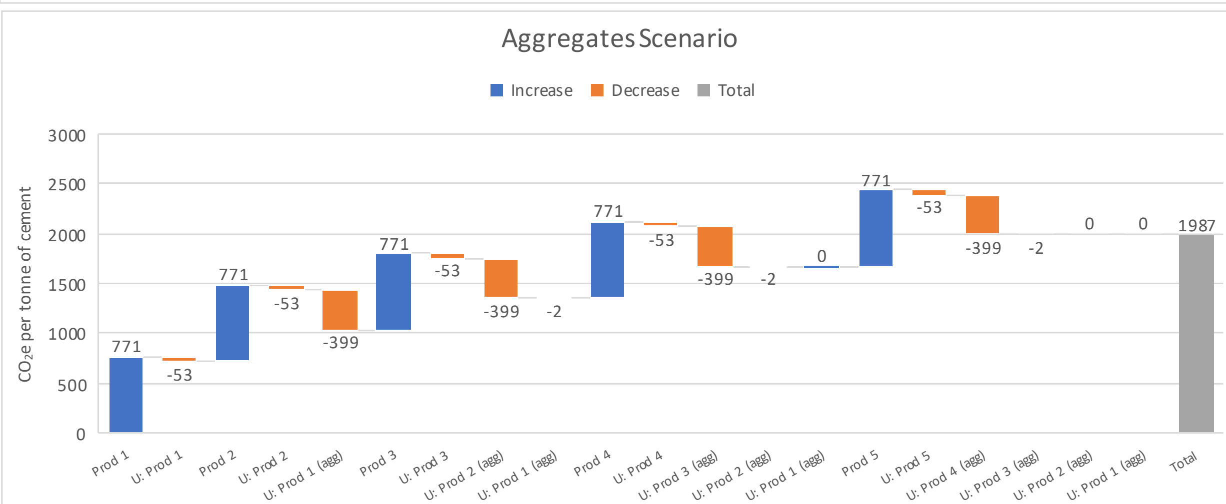
| | | | |
|---|---|---|---|
| Additive CO2 After 20 years | 717.51 | 717.51 | 717.51 |
| Additive CO2 After 40 years | 1,371.78 | 1,431.85 | 1,038.12 |
| Additive CO2 After 60 years | 2,026.04 | 2,146.19 | 1,356.99 |
| Additive CO2 After 80 years | 2,680.30 | 2,860.53 | 1,675.85 |
| Additive CO2 After 100 years | 3,334.56 | 3,574.87 | 1,994.72 |

*Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*
*Jurisdiction: Canada; Service Life: 20 years*

| **Primary** | **Secondary** | **Strength** |
|---|---|---|
| **Indoors** | **Exposed** | **> 35 MPa** |



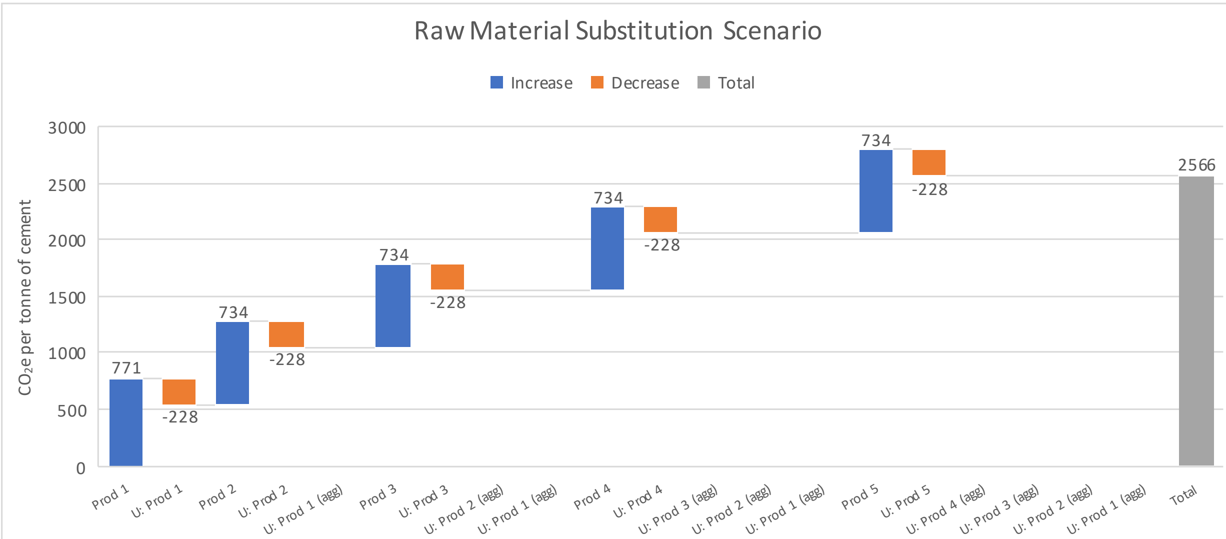
*Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*
*Jurisdiction: Canada; Service Life: 20 years*

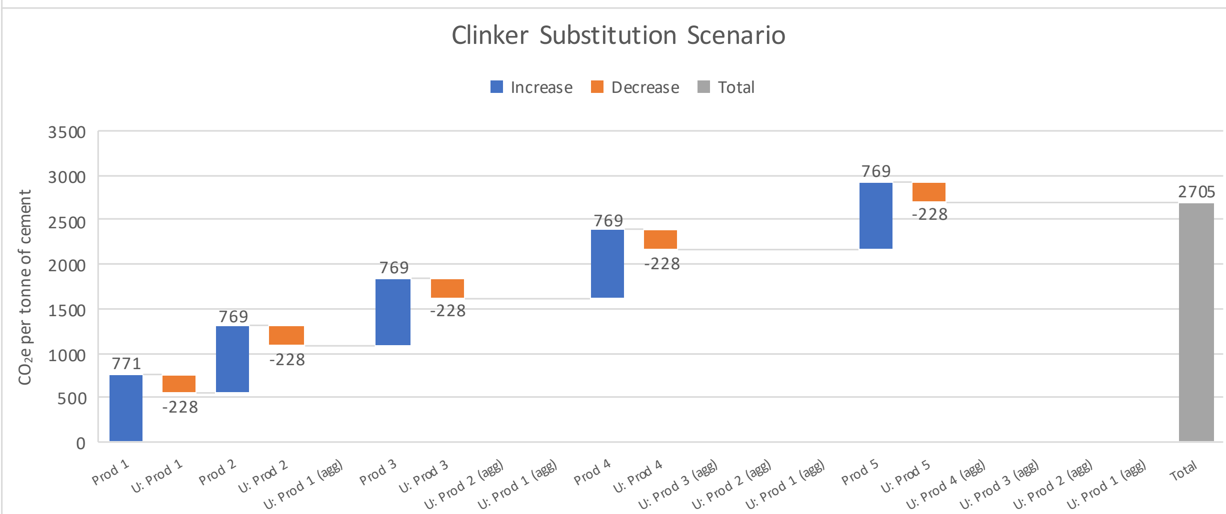
| | Primary Indoors | Secondary Buried | Strength <15 MPa |
|---|---|---|---|
| **Substituion Type** | **Raw Material** | **Clinker** | **Aggregates** |
| 1st Production | 771 | 771 | 771 |
| CO2 Uptake Year 0 to 20 | -228 | -228 | -228 |
| 2nd Production | 734 | 769 | 771 |
| CO2 Uptake for Year 21 to 40 (2nd Production) | -228 | -228 | -228 |
| CO2 Uptake for Year 21 to 40 (1st Production Aggregates) | | | -226 |
| 3rd Production | 734 | 769 | 771 |
| CO2 Uptake for Year 41 to 60 (3rd Production) | -228 | -228 | -228 |
| CO2 Uptake for Year 41 to 60 (2nd Production Aggregates) | | | -226 |
| CO2 Uptake for Year 41 to 60 (1st Production Aggregates) | | | 0 |
| 4th Production | 734 | 769 | 771 |
| CO2 Uptake for Year 61 to 80 (4th Production) | -228 | -228 | -228 |
| CO2 Uptake for Year 61 to 80 (3rd Production Aggregates) | | | -226 |
| CO2 Uptake for Year 61 to 80 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 61 to 80 (1st Production Aggregates) | | | 0 |
| 5th Production | 734 | 769 | 771 |
| CO2 Uptake for Year 81 to 100 (4th Production) | -228 | -228 | -228 |
| CO2 Uptake for Year 81 to 100 (4th Production Aggregates) | | | -226 |
| CO2 Uptake for Year 81 to 100 (3rd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (1st Production Aggregates) | | | 0 |
| Total Additive CO2 after 100 years | 2566 | 2705 | 1810 |

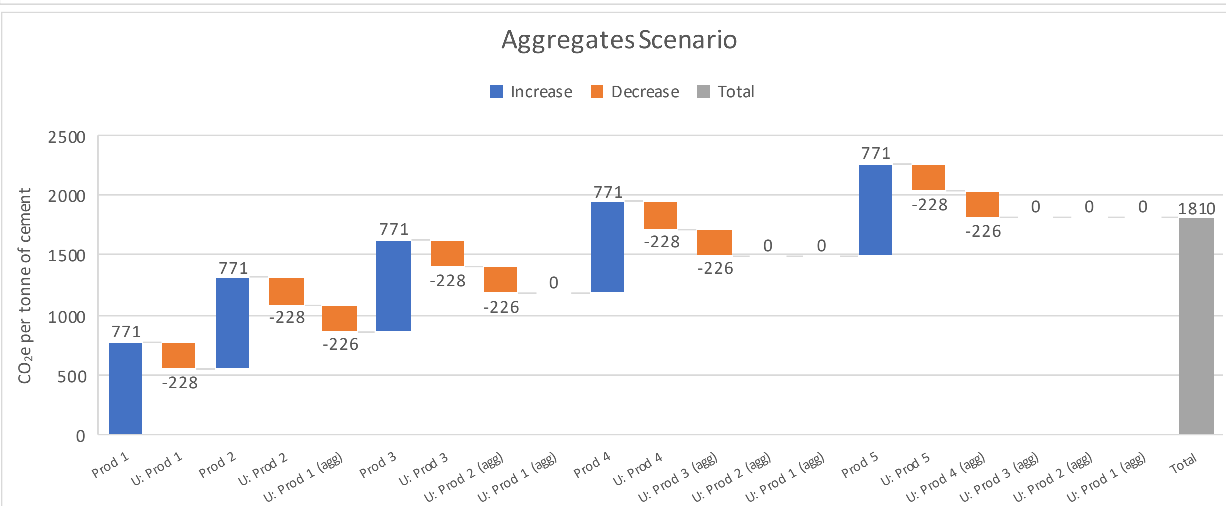
| | | | |
|---|---|---|---|
| Additive CO2 After 20 years | 542.40 | 542.40 | 542.40 |
| Additive CO2 After 40 years | 1,048.42 | 1,083.08 | 861.27 |
| Additive CO2 After 60 years | 1,554.44 | 1,623.77 | 1,180.13 |
| Additive CO2 After 80 years | 2,060.46 | 2,164.45 | 1,499.00 |
| Additive CO2 After 100 years | 2,566.48 | 2,705.13 | 1,817.86 |

*Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*
*Jurisdiction: Canada; Service Life: 20 years*

| Primary | Secondary | Strength |
|---|---|---|
| Indoors | Buried | <15 MPa |



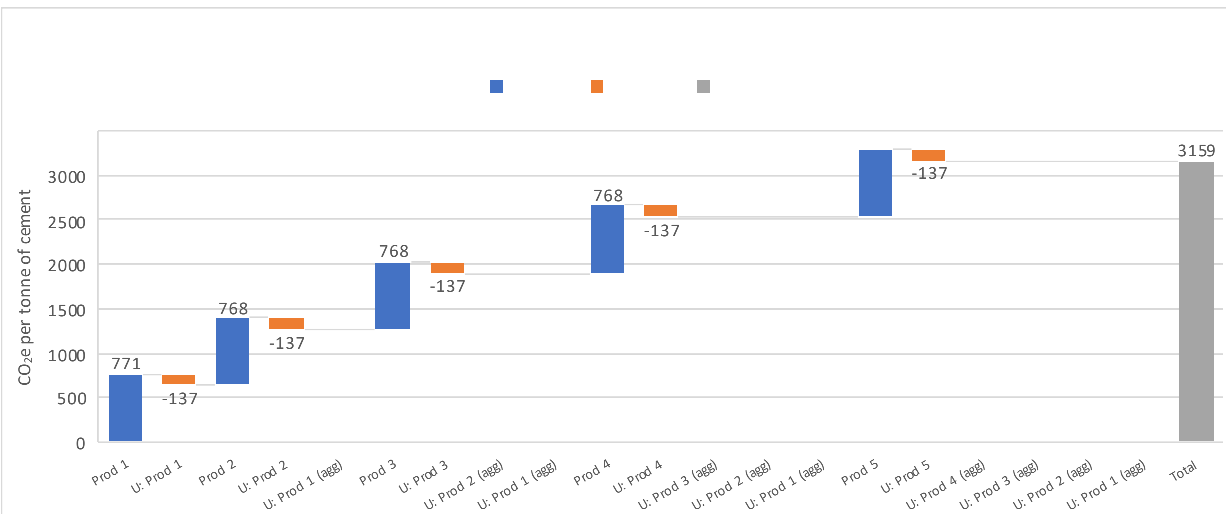



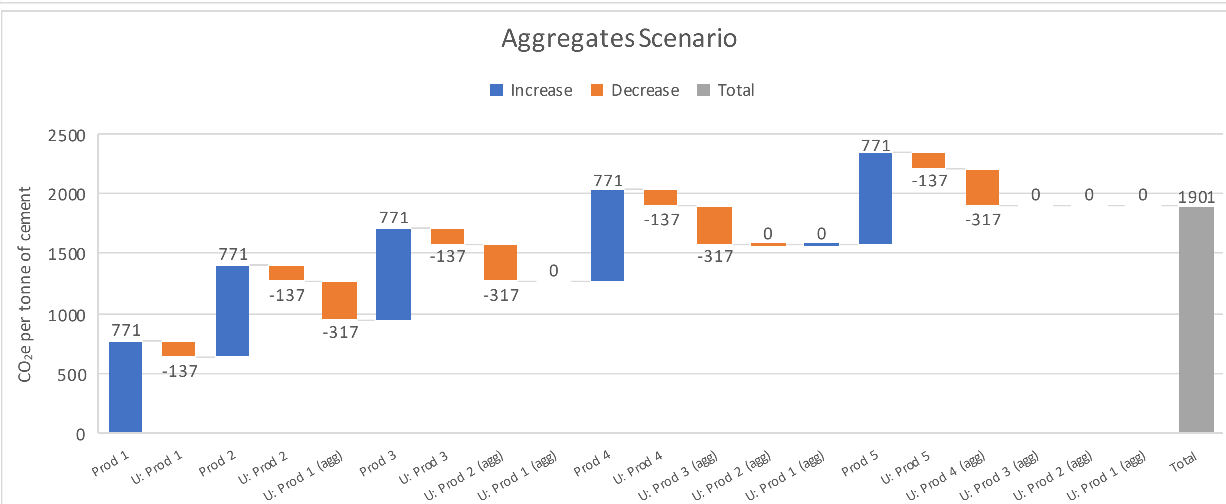
| *Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm<br>Jurisdiction: Canada; Service Life: 20 years* | **Primary**<br>**Indoors** | **Secondary**<br>**Buried** | **Strength**<br>**15-20 MPa** |
|---|---|---|---|
| **Substituion Type** | **Raw Material** | **Clinker** | **Aggregates** |
| 1st Production | 771 | 771 | 771 |
| CO2 Uptake Year 0 to 20 | -137 | -137 | -137 |
| 2nd Production | 720 | 768 | 771 |
| CO2 Uptake for Year 21 to 40 (2nd Production) | -137 | -137 | -137 |
| CO2 Uptake for Year 21 to 40 (1st Production Aggregates) | | | -317 |
| 3rd Production | 720 | 768 | 771 |
| CO2 Uptake for Year 41 to 60 (3rd Production) | -137 | -137 | -137 |
| CO2 Uptake for Year 41 to 60 (2nd Production Aggregates) | | | -317 |
| CO2 Uptake for Year 41 to 60 (1st Production Aggregates) | | | 0 |
| 4th Production | 720 | 768 | 771 |
| CO2 Uptake for Year 61 to 80 (4th Production) | -137 | -137 | -137 |
| CO2 Uptake for Year 61 to 80 (3rd Production Aggregates) | | | -317 |
| CO2 Uptake for Year 61 to 80 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 61 to 80 (1st Production Aggregates) | | | 0 |
| 5th Production | 720 | 768 | 771 |
| CO2 Uptake for Year 81 to 100 (4th Production) | -137 | -137 | -137 |
| CO2 Uptake for Year 81 to 100 (4th Production Aggregates) | | | -317 |
| CO2 Uptake for Year 81 to 100 (3rd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (1st Production Aggregates) | | | 0 |
| Total Additive CO2 after 100 years | 2967 | 3159 | 1901 |

| | | | |
|---|---|---|---|
| Additive CO2 After 20 years | 633.76 | 633.76 | 633.76 |
| Additive CO2 After 40 years | 1,216.98 | 1,265.07 | 952.63 |
| Additive CO2 After 60 years | 1,800.20 | 1,896.37 | 1,271.49 |
| Additive CO2 After 80 years | 2,383.42 | 2,527.67 | 1,590.36 |
| Additive CO2 After 100 years | 2,966.64 | 3,158.97 | 1,909.22 |

*Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*
*Jurisdiction: Canada; Service Life: 20 years*

| Primary | Secondary | Strength |
|---|---|---|
| Indoors | Buried | 15-20 MPa |



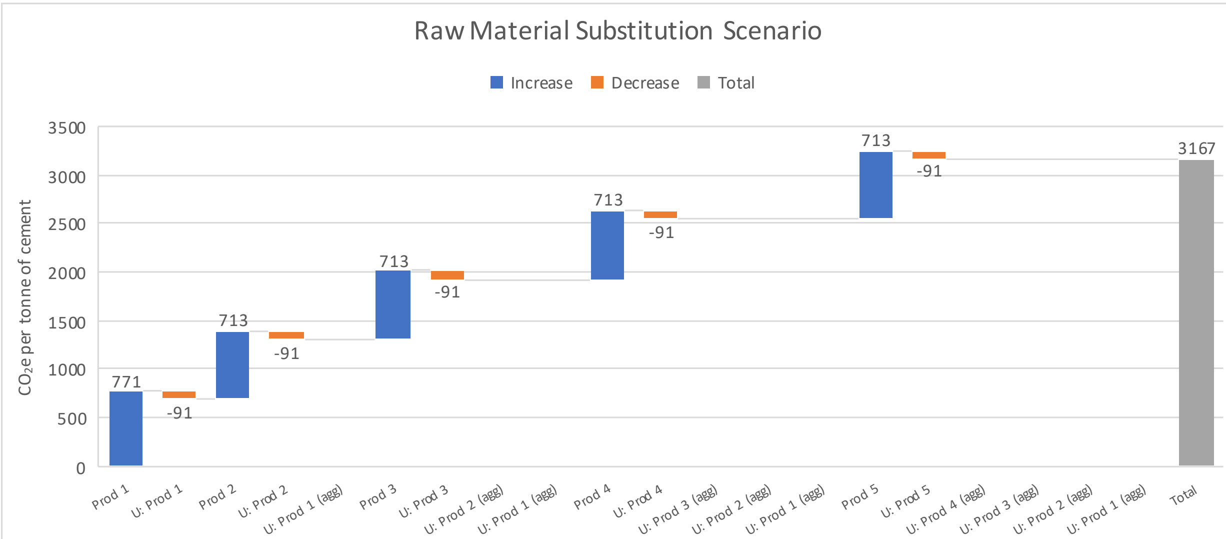



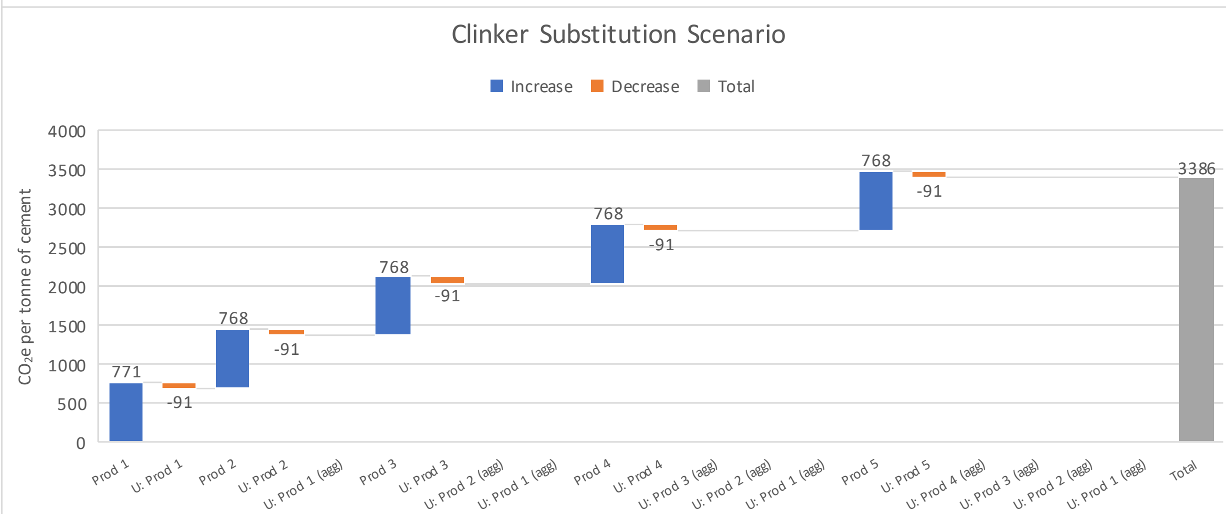
| *Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*<br>*Jurisdiction: Canada; Service Life: 20 years* | **Primary**<br>**Indoors** | **Secondary**<br>**Buried** | **Strength**<br>**25-30 MPa** |
|---|---|---|---|
| **Substituion Type** | **Raw Material** | **Clinker** | **Aggregates** |
| 1st Production | 771 | 771 | 771 |
| CO2 Uptake Year 0 to 20 | -91 | -91 | -91 |
| 2nd Production | 713 | 768 | 771 |
| CO2 Uptake for Year 21 to 40 (2nd Production) | -91 | -91 | -91 |
| CO2 Uptake for Year 21 to 40 (1st Production Aggregates) | | | -363 |
| 3rd Production | 713 | 768 | 771 |
| CO2 Uptake for Year 41 to 60 (3rd Production) | -91 | -91 | -91 |
| CO2 Uptake for Year 41 to 60 (2nd Production Aggregates) | | | -363 |
| CO2 Uptake for Year 41 to 60 (1st Production Aggregates) | | | 0 |
| 4th Production | 713 | 768 | 771 |
| CO2 Uptake for Year 61 to 80 (4th Production) | -91 | -91 | -91 |
| CO2 Uptake for Year 61 to 80 (3rd Production Aggregates) | | | -363 |
| CO2 Uptake for Year 61 to 80 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 61 to 80 (1st Production Aggregates) | | | 0 |
| 5th Production | 713 | 768 | 771 |
| CO2 Uptake for Year 81 to 100 (4th Production) | -91 | -91 | -91 |
| CO2 Uptake for Year 81 to 100 (4th Production Aggregates) | | | -363 |
| CO2 Uptake for Year 81 to 100 (3rd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (1st Production Aggregates) | | | 0 |
| Total Additive CO2 after 100 years | 3167 | 3386 | 1947 |

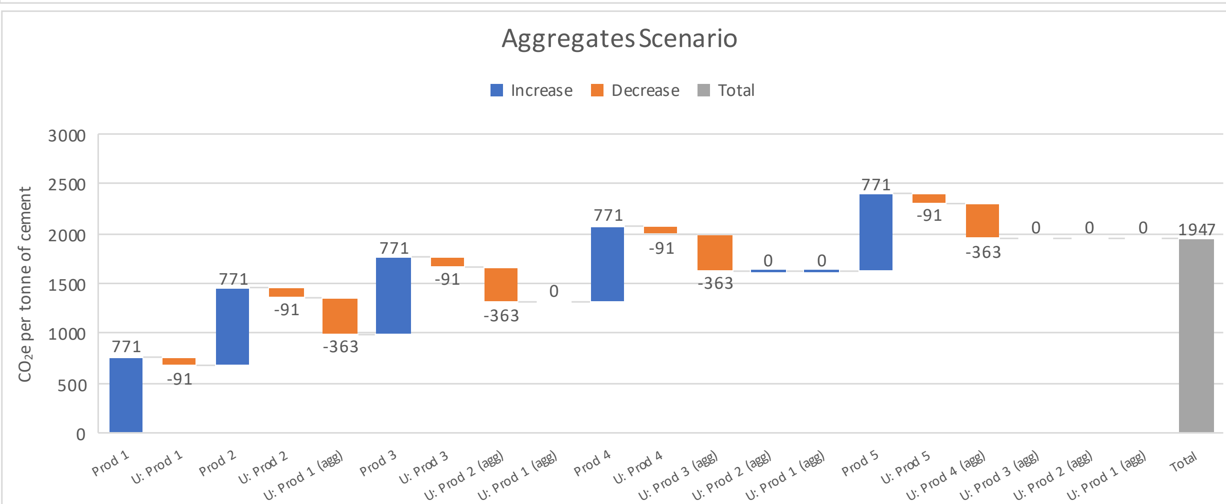
| | | | |
|---|---|---|---|
| Additive CO2 After 20 years | 679.45 | 679.45 | 679.45 |
| Additive CO2 After 40 years | 1,301.38 | 1,356.04 | 998.31 |
| Additive CO2 After 60 years | 1,923.32 | 2,032.64 | 1,317.18 |
| Additive CO2 After 80 years | 2,545.26 | 2,709.24 | 1,636.04 |
| Additive CO2 After 100 years | 3,167.19 | 3,385.84 | 1,954.91 |

*Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*
*Jurisdiction: Canada; Service Life: 20 years*

| Primary | Secondary | Strength |
|---|---|---|
| **Indoors** | **Buried** | **25-30 MPa** |



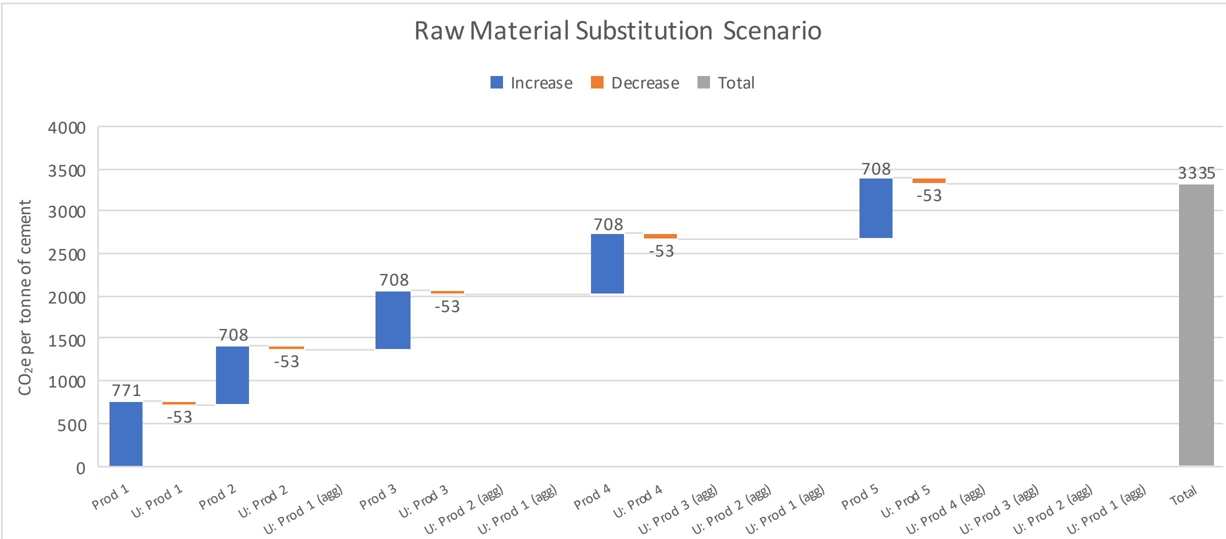
*Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*
*Jurisdiction: Canada; Service Life: 20 years*

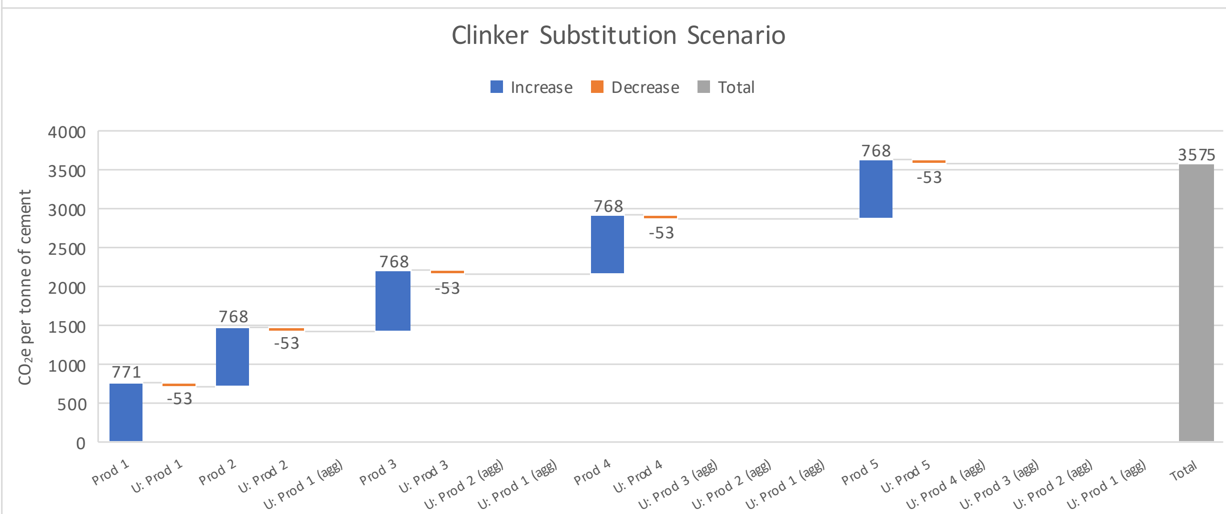
| | **Primary Indoors** | **Secondary Buried** | **Strength > 35 MPa** |
|---|---|---|---|
| **Substituion Type** | **Raw Material** | **Clinker** | **Aggregates** |
| 1st Production | 771 | 771 | 771 |
| CO2 Uptake Year 0 to 20 | -53 | -53 | -53 |
| 2nd Production | 708 | 768 | 771 |
| CO2 Uptake for Year 21 to 40 (2nd Production) | -53 | -53 | -53 |
| CO2 Uptake for Year 21 to 40 (1st Production Aggregates) | | | -299 |
| 3rd Production | 708 | 768 | 771 |
| CO2 Uptake for Year 41 to 60 (3rd Production) | -53 | -53 | -53 |
| CO2 Uptake for Year 41 to 60 (2nd Production Aggregates) | | | -299 |
| CO2 Uptake for Year 41 to 60 (1st Production Aggregates) | | | -101 |
| 4th Production | 708 | 768 | 771 |
| CO2 Uptake for Year 61 to 80 (4th Production) | -53 | -53 | -53 |
| CO2 Uptake for Year 61 to 80 (3rd Production Aggregates) | | | -299 |
| CO2 Uptake for Year 61 to 80 (2nd Production Aggregates) | | | -101 |
| CO2 Uptake for Year 61 to 80 (1st Production Aggregates) | | | 0 |
| 5th Production | 708 | 768 | 771 |
| CO2 Uptake for Year 81 to 100 (4th Production) | -53 | -53 | -53 |
| CO2 Uptake for Year 81 to 100 (4th Production Aggregates) | | | -299 |
| CO2 Uptake for Year 81 to 100 (3rd Production Aggregates) | | | -101 |
| CO2 Uptake for Year 81 to 100 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (1st Production Aggregates) | | | 0 |
| Total Additive CO2 after 100 years | 3335 | 3575 | 2086 |

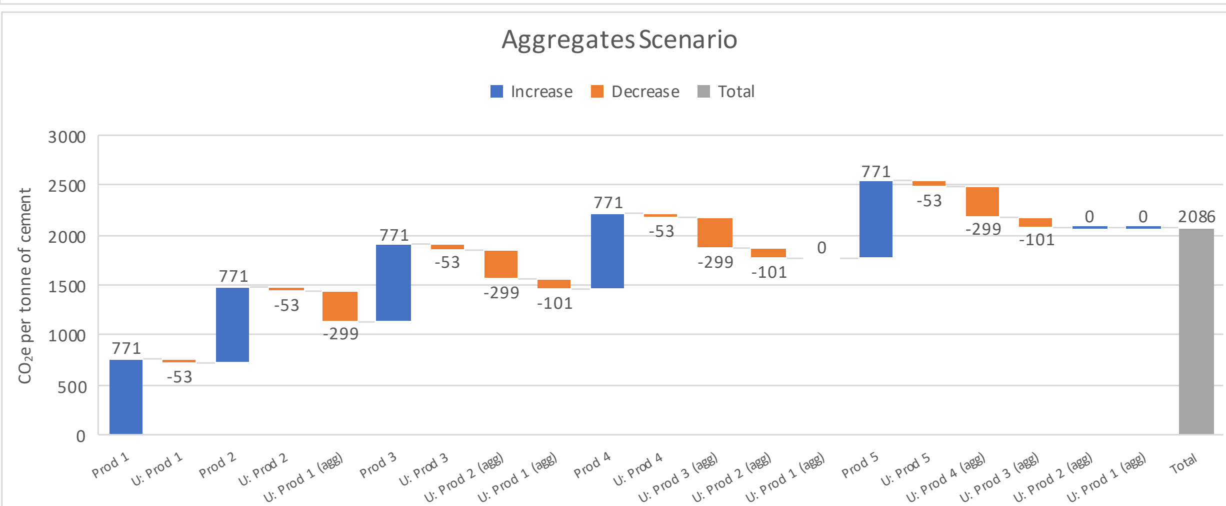
| | | | |
|---|---|---|---|
| Additive CO2 After 20 years | 717.51 | 717.51 | 717.51 |
| Additive CO2 After 40 years | 1,371.78 | 1,431.85 | 1,137.86 |
| Additive CO2 After 60 years | 2,026.04 | 2,146.19 | 1,456.72 |
| Additive CO2 After 80 years | 2,680.30 | 2,860.53 | 1,775.59 |
| Additive CO2 After 100 years | 3,334.56 | 3,574.87 | 2,094.45 |

*Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*
*Jurisdiction: Canada; Service Life: 20 years*

| Primary | Secondary | Strength |
|---|---|---|
| Indoors | Buried | > 35 MPa |



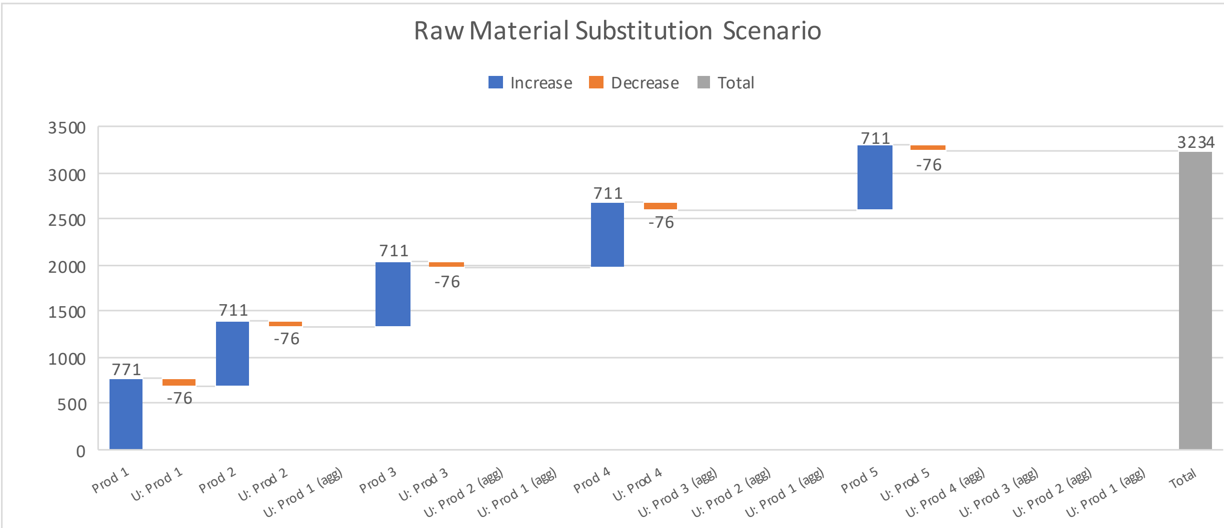



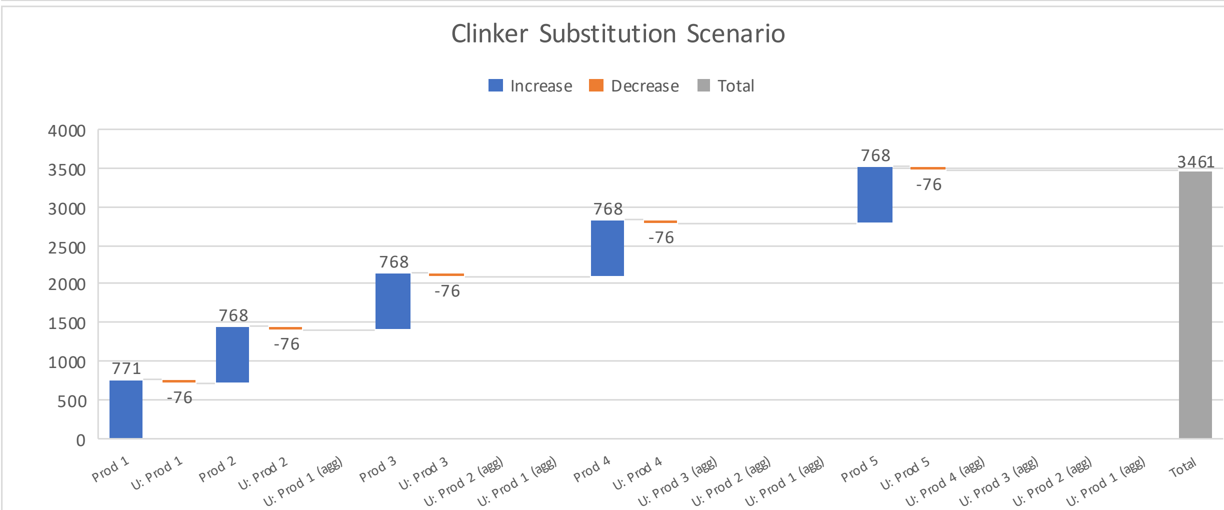
| *Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm<br>Jurisdiction: Canada; Service Life: 20 years* | **Primary<br>Exposed** | **Secondary<br>Exposed** | **Strength<br><15 MPa** |
|---|---|---|---|
| **Substituion Type** | **Raw Material** | **Clinker** | **Aggregates** |
| 1st Production | 771 | 771 | 771 |
| CO2 Uptake Year 0 to 20 | -76 | -76 | -76 |
| 2nd Production | 711 | 768 | 771 |
| CO2 Uptake for Year 21 to 40 (2nd Production) | -76 | -76 | -76 |
| CO2 Uptake for Year 21 to 40 (1st Production Aggregates) | | | -378 |
| 3rd Production | 711 | 768 | 771 |
| CO2 Uptake for Year 41 to 60 (3rd Production) | -76 | -76 | -76 |
| CO2 Uptake for Year 41 to 60 (2nd Production Aggregates) | | | -378 |
| CO2 Uptake for Year 41 to 60 (1st Production Aggregates) | | | 0 |
| 4th Production | 711 | 768 | 771 |
| CO2 Uptake for Year 61 to 80 (4th Production) | -76 | -76 | -76 |
| CO2 Uptake for Year 61 to 80 (3rd Production Aggregates) | | | -378 |
| CO2 Uptake for Year 61 to 80 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 61 to 80 (1st Production Aggregates) | | | 0 |
| 5th Production | 711 | 768 | 771 |
| CO2 Uptake for Year 81 to 100 (4th Production) | -76 | -76 | -76 |
| CO2 Uptake for Year 81 to 100 (4th Production Aggregates) | | | -378 |
| CO2 Uptake for Year 81 to 100 (3rd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (1st Production Aggregates) | | | 0 |
| Total Additive CO2 after 100 years | 3234 | 3461 | 1962 |

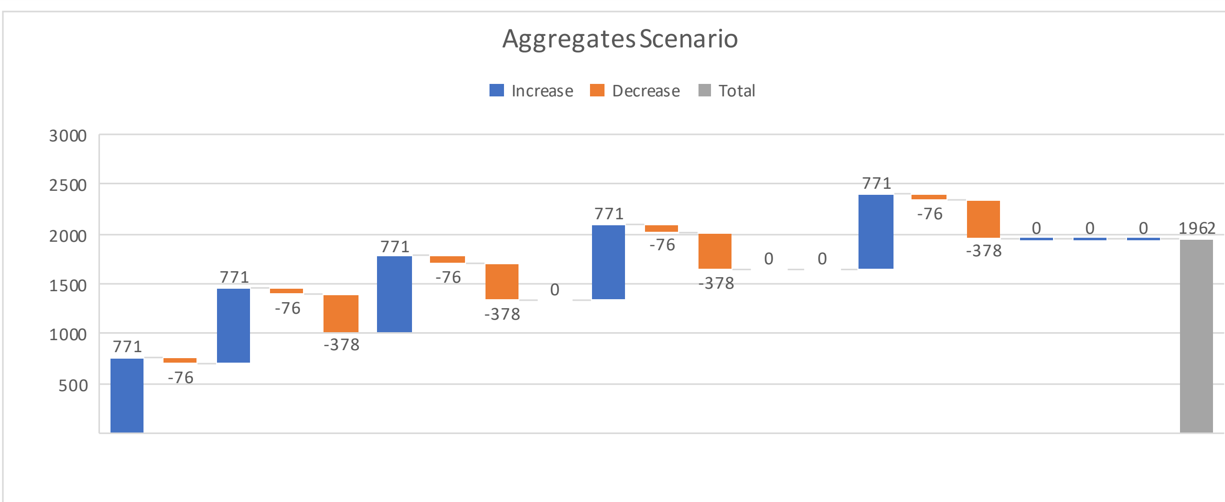
| | | | |
|---|---|---|---|
| Additive CO2 After 20 years | 694.67 | 694.67 | 694.67 |
| Additive CO2 After 40 years | 1,329.53 | 1,386.37 | 1,013.54 |
| Additive CO2 After 60 years | 1,964.39 | 2,078.06 | 1,332.40 |
| Additive CO2 After 80 years | 2,599.25 | 2,769.76 | 1,651.27 |
| Additive CO2 After 100 years | 3,234.11 | 3,461.45 | 1,970.13 |

*Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*
*Jurisdiction: Canada; Service Life: 20 years*

| Primary | Secondary | Strength |
|---|---|---|
| Exposed | Exposed | <15 MPa |



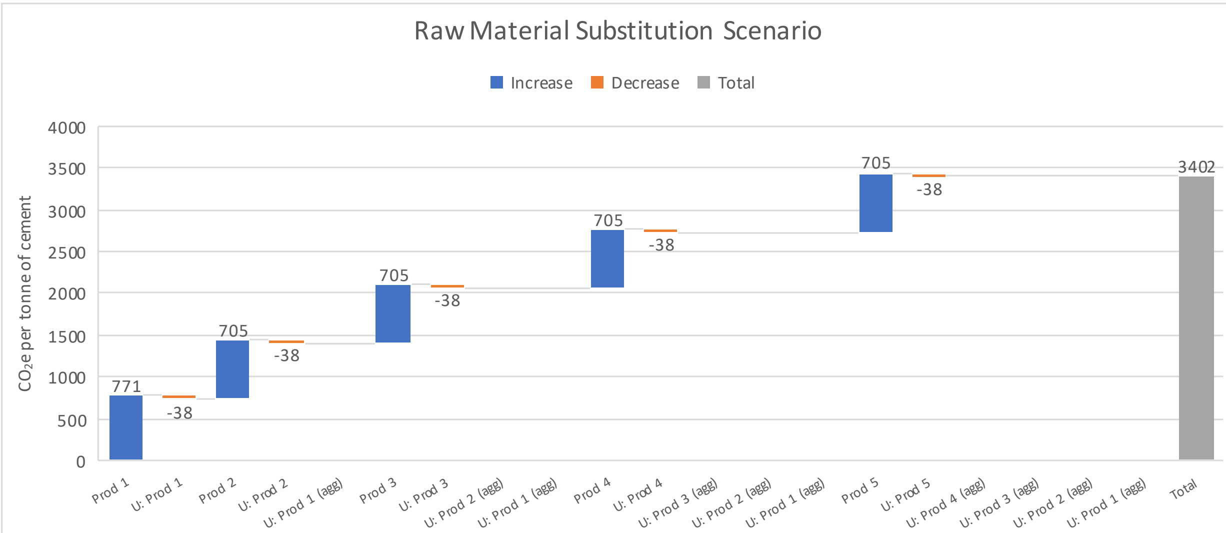



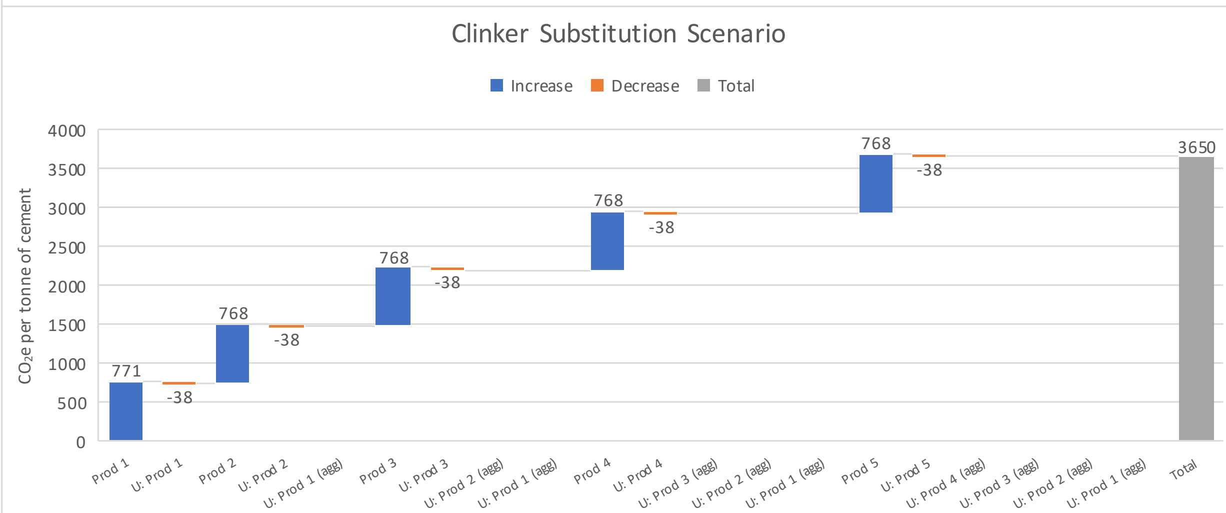
| *Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm Jurisdiction: Canada; Service Life: 20 years* | **Primary Exposed** | **Secondary Exposed** | **Strength 15-20 MPa** |
|---|---|---|---|
| **Substituion Type** | **Raw Material** | **Clinker** | **Aggregates** |
| 1st Production | 771 | 771 | 771 |
| CO2 Uptake Year 0 to 20 | -38 | -38 | -38 |
| 2nd Production | 705 | 768 | 771 |
| CO2 Uptake for Year 21 to 40 (2nd Production) | -38 | -38 | -38 |
| CO2 Uptake for Year 21 to 40 (1st Production Aggregates) | | | -416 |
| 3rd Production | 705 | 768 | 771 |
| CO2 Uptake for Year 41 to 60 (3rd Production) | -38 | -38 | -38 |
| CO2 Uptake for Year 41 to 60 (2nd Production Aggregates) | | | -416 |
| CO2 Uptake for Year 41 to 60 (1st Production Aggregates) | | | 0 |
| 4th Production | 705 | 768 | 771 |
| CO2 Uptake for Year 61 to 80 (4th Production) | -38 | -38 | -38 |
| CO2 Uptake for Year 61 to 80 (3rd Production Aggregates) | | | -416 |
| CO2 Uptake for Year 61 to 80 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 61 to 80 (1st Production Aggregates) | | | 0 |
| 5th Production | 705 | 768 | 771 |
| CO2 Uptake for Year 81 to 100 (4th Production) | -38 | -38 | -38 |
| CO2 Uptake for Year 81 to 100 (4th Production Aggregates) | | | -416 |
| CO2 Uptake for Year 81 to 100 (3rd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (1st Production Aggregates) | | | 0 |
| Total Additive CO2 after 100 years | 3402 | 3650 | 2000 |

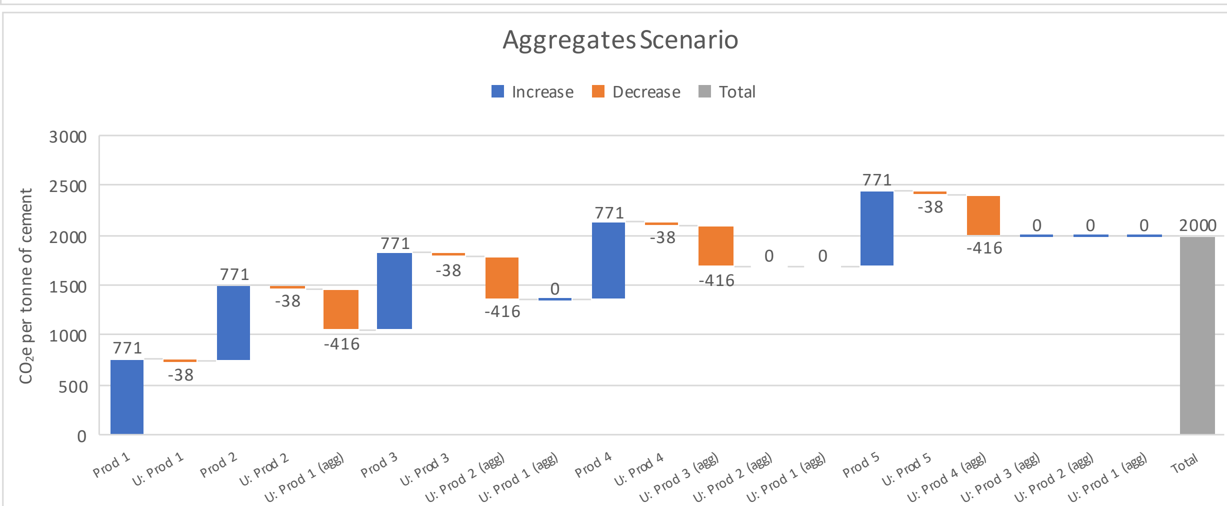
| | | | |
|---|---|---|---|
| Additive CO2 After 20 years | 732.74 | 732.74 | 732.74 |
| Additive CO2 After 40 years | 1,399.95 | 1,462.17 | 1,051.61 |
| Additive CO2 After 60 years | 2,067.15 | 2,191.61 | 1,370.47 |
| Additive CO2 After 80 years | 2,734.36 | 2,921.04 | 1,689.34 |
| Additive CO2 After 100 years | 3,401.56 | 3,650.47 | 2,008.20 |

*Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*
*Jurisdiction: Canada; Service Life: 20 years*

| Primary Exposed | Secondary Exposed | Strength 15-20 MPa |
|---|---|---|



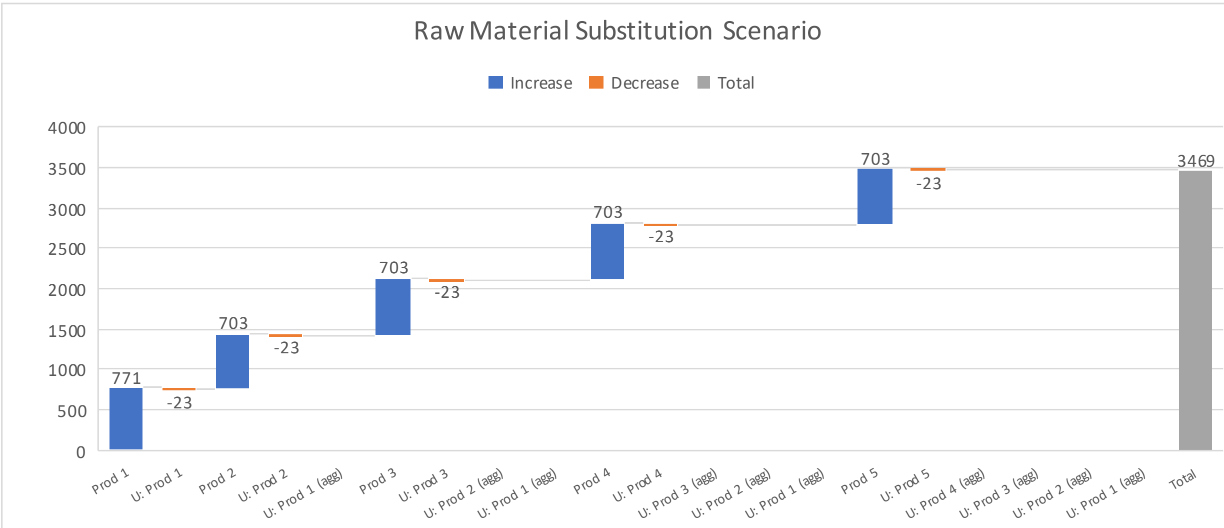



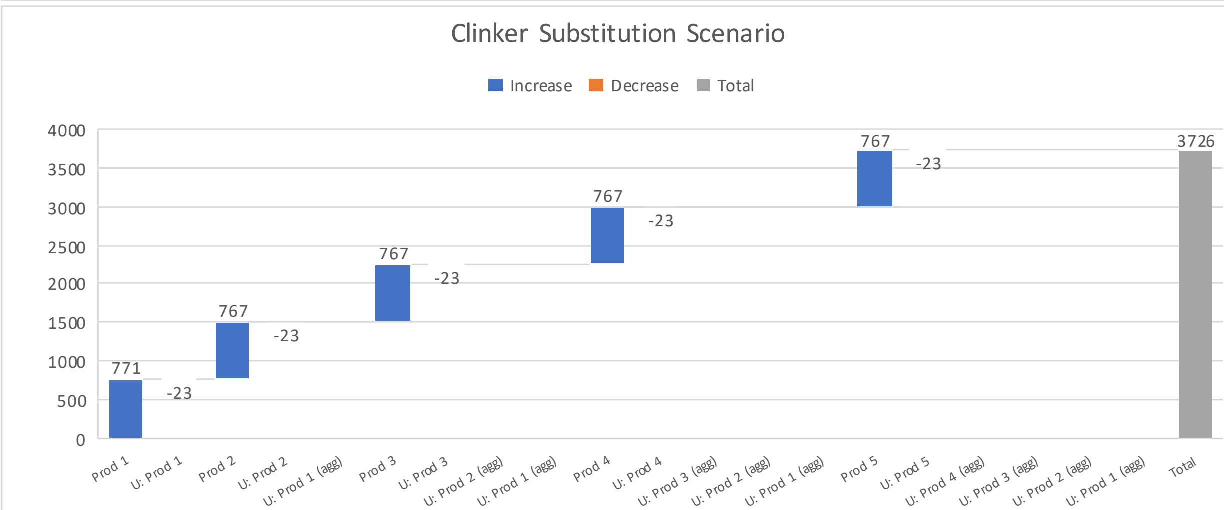
| *Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*<br>*Jurisdiction: Canada; Service Life: 20 years* | **Primary**<br>**Exposed** | **Secondary**<br>**Exposed** | **Strength**<br>**25-30 MPa** |
|---|---|---|---|
| **Substituion Type** | **Raw Material** | **Clinker** | **Aggregates** |
| 1st Production | 771 | 771 | 771 |
| CO2 Uptake Year 0 to 20 | -23 | -23 | -23 |
| 2nd Production | 703 | 767 | 771 |
| CO2 Uptake for Year 21 to 40 (2nd Production) | -23 | -23 | -23 |
| CO2 Uptake for Year 21 to 40 (1st Production Aggregates) | | | -431 |
| 3rd Production | 703 | 767 | 771 |
| CO2 Uptake for Year 41 to 60 (3rd Production) | -23 | -23 | -23 |
| CO2 Uptake for Year 41 to 60 (2nd Production Aggregates) | | | -431 |
| CO2 Uptake for Year 41 to 60 (1st Production Aggregates) | | | 0 |
| 4th Production | 703 | 767 | 771 |
| CO2 Uptake for Year 61 to 80 (4th Production) | -23 | -23 | -23 |
| CO2 Uptake for Year 61 to 80 (3rd Production Aggregates) | | | -431 |
| CO2 Uptake for Year 61 to 80 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 61 to 80 (1st Production Aggregates) | | | 0 |
| 5th Production | 703 | 767 | 771 |
| CO2 Uptake for Year 81 to 100 (4th Production) | -23 | -23 | -23 |
| CO2 Uptake for Year 81 to 100 (4th Production Aggregates) | | | -431 |
| CO2 Uptake for Year 81 to 100 (3rd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (1st Production Aggregates) | | | 0 |
| Total Additive CO2 after 100 years | 3469 | 3726 | 2015 |

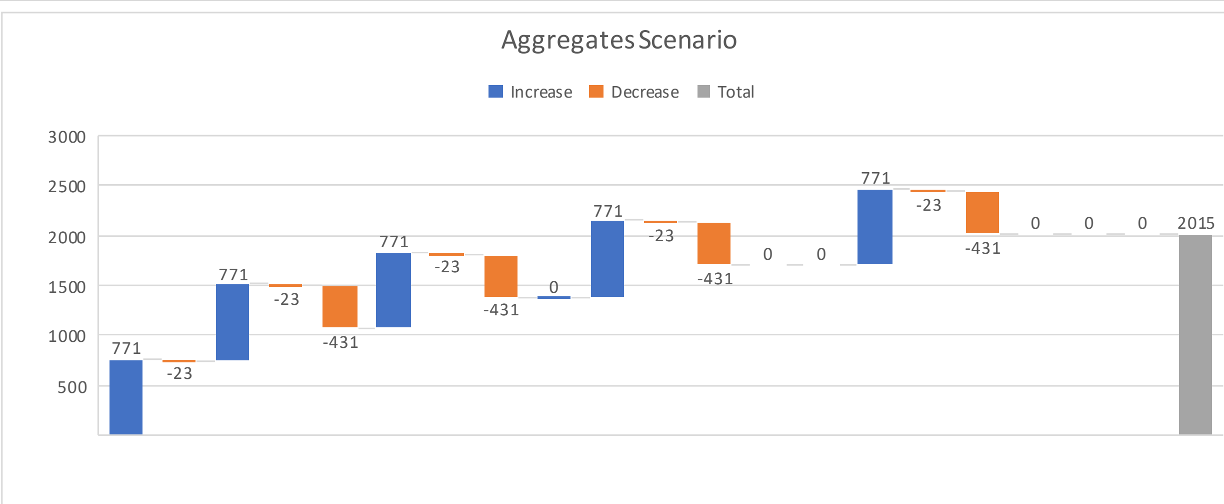
| | | | |
|---|---|---|---|
| Additive CO2 After 20 years | 747.97 | 747.97 | 747.97 |
| Additive CO2 After 40 years | 1,428.13 | 1,492.50 | 1,066.83 |
| Additive CO2 After 60 years | 2,108.28 | 2,237.02 | 1,385.70 |
| Additive CO2 After 80 years | 2,788.44 | 2,981.55 | 1,704.56 |
| Additive CO2 After 100 years | 3,468.60 | 3,726.08 | 2,023.43 |

*Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*
*Jurisdiction: Canada; Service Life: 20 years*

| Primary | Secondary | Strength |
|---|---|---|
| Exposed | Exposed | 25-30 MPa |



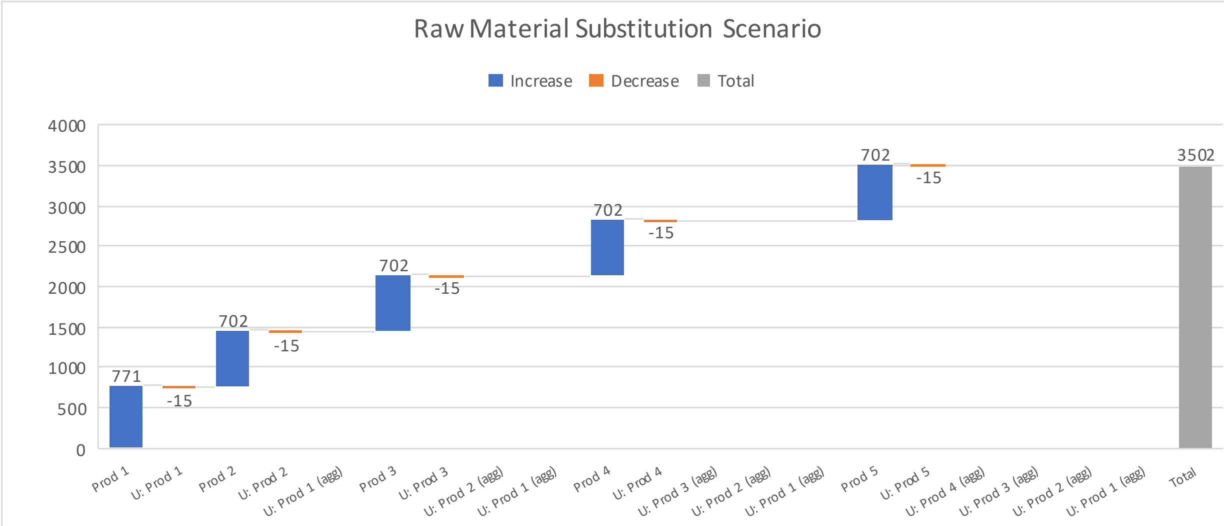
*Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*
*Jurisdiction: Canada; Service Life: 20 years*

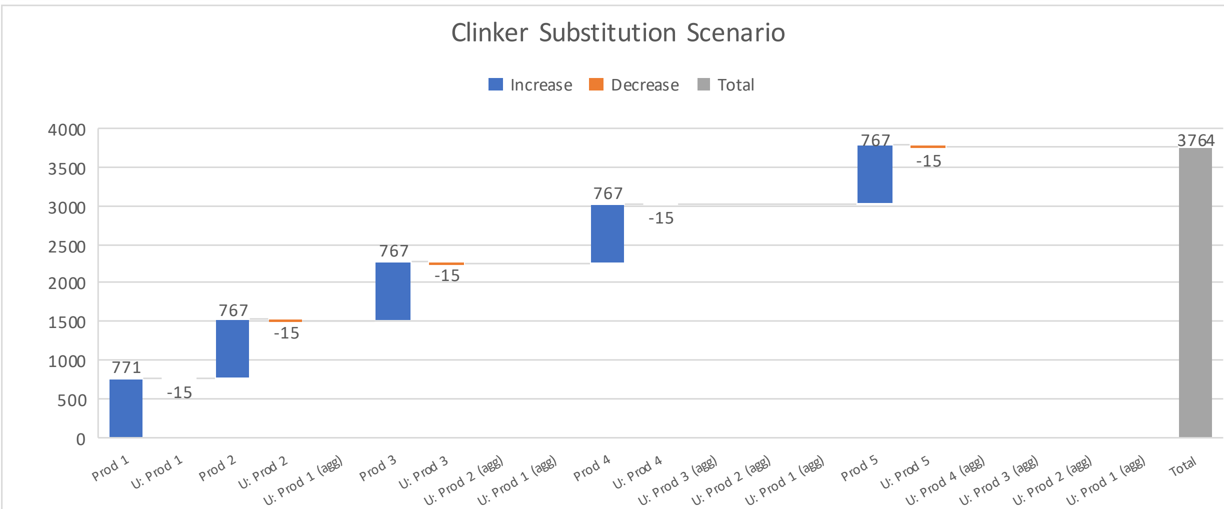
| | Primary Exposed | Secondary Exposed | Strength > 35 MPa |
|---|---|---|---|
| **Substituion Type** | **Raw Material** | **Clinker** | **Aggregates** |
| 1st Production | 771 | 771 | 771 |
| CO2 Uptake Year 0 to 20 | -15 | -15 | -15 |
| 2nd Production | 702 | 767 | 771 |
| CO2 Uptake for Year 21 to 40 (2nd Production) | -15 | -15 | -15 |
| CO2 Uptake for Year 21 to 40 (1st Production Aggregates) | | | -399 |
| 3rd Production | 702 | 767 | 771 |
| CO2 Uptake for Year 41 to 60 (3rd Production) | -15 | -15 | -15 |
| CO2 Uptake for Year 41 to 60 (2nd Production Aggregates) | | | -399 |
| CO2 Uptake for Year 41 to 60 (1st Production Aggregates) | | | -40 |
| 4th Production | 702 | 767 | 771 |
| CO2 Uptake for Year 61 to 80 (4th Production) | -15 | -15 | -15 |
| CO2 Uptake for Year 61 to 80 (3rd Production Aggregates) | | | -399 |
| CO2 Uptake for Year 61 to 80 (2nd Production Aggregates) | | | -40 |
| CO2 Uptake for Year 61 to 80 (1st Production Aggregates) | | | 0 |
| 5th Production | 702 | 767 | 771 |
| CO2 Uptake for Year 81 to 100 (4th Production) | -15 | -15 | -15 |
| CO2 Uptake for Year 81 to 100 (4th Production Aggregates) | | | -399 |
| CO2 Uptake for Year 81 to 100 (3rd Production Aggregates) | | | -40 |
| CO2 Uptake for Year 81 to 100 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (1st Production Aggregates) | | | 0 |
| Total Additive CO2 after 100 years | 3502 | 3764 | 2063 |

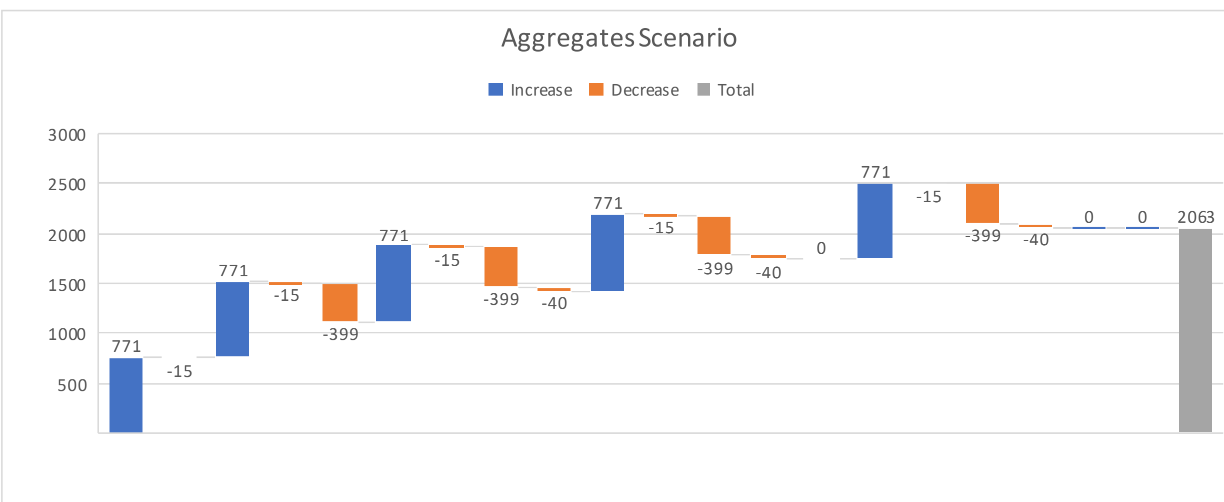
| | | | |
|---|---|---|---|
| Additive CO2 After 20 years | 755.58 | 755.58 | 755.58 |
| Additive CO2 After 40 years | 1,442.22 | 1,507.66 | 1,114.26 |
| Additive CO2 After 60 years | 2,128.86 | 2,259.73 | 1,433.12 |
| Additive CO2 After 80 years | 2,815.49 | 3,011.80 | 1,751.99 |
| Additive CO2 After 100 years | 3,502.13 | 3,763.88 | 2,070.85 |

*Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*
*Jurisdiction: Canada; Service Life: 20 years*

| Primary Exposed | Secondary Exposed | Strength > 35 MPa |
|---|---|---|



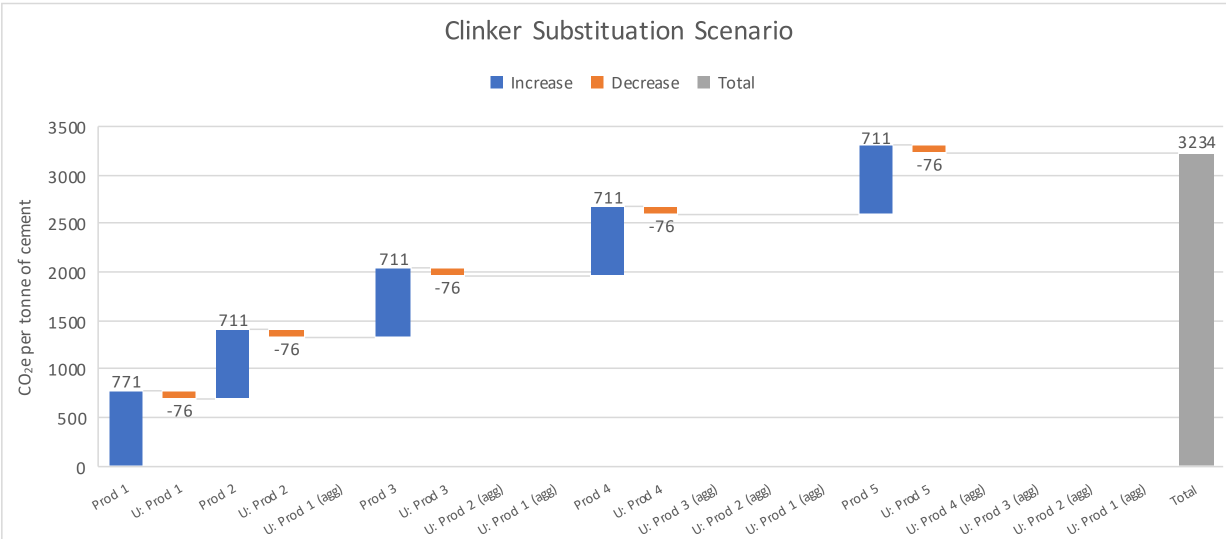



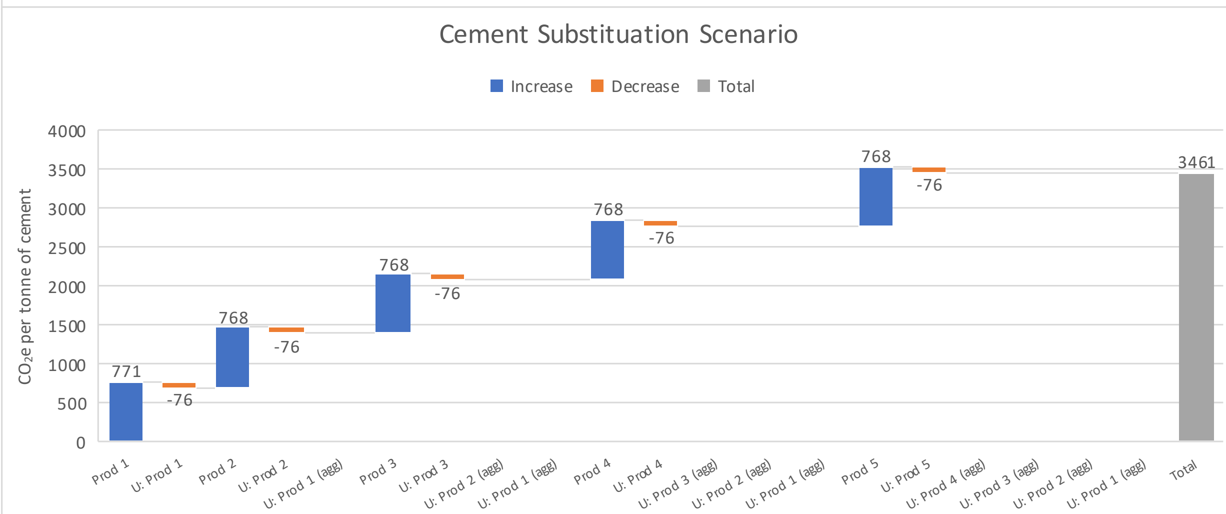
| *Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*<br>*Jurisdiction: Canada; Service Life: 20 years* | **Primary**<br>**Exposed** | **Secondary**<br>**Buried** | **Strength**<br>**<15 MPa** |
|---|---|---|---|
| **Substituion Type** | **Raw Material** | **Clinker** | **Aggregates** |
| 1st Production | 771 | 771 | 771 |
| CO2 Uptake Year 0 to 20 | -76 | -76 | -76 |
| 2nd Production | 711 | 768 | 771 |
| CO2 Uptake for Year 21 to 40 (2nd Production) | -76 | -76 | -76 |
| CO2 Uptake for Year 21 to 40 (1st Production Aggregates) | | | -378 |
| 3rd Production | 711 | 768 | 771 |
| CO2 Uptake for Year 41 to 60 (3rd Production) | -76 | -76 | -76 |
| CO2 Uptake for Year 41 to 60 (2nd Production Aggregates) | | | -378 |
| CO2 Uptake for Year 41 to 60 (1st Production Aggregates) | | | 0 |
| 4th Production | 711 | 768 | 771 |
| CO2 Uptake for Year 61 to 80 (4th Production) | -76 | -76 | -76 |
| CO2 Uptake for Year 61 to 80 (3rd Production Aggregates) | | | -378 |
| CO2 Uptake for Year 61 to 80 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 61 to 80 (1st Production Aggregates) | | | 0 |
| 5th Production | 711 | 768 | 771 |
| CO2 Uptake for Year 81 to 100 (4th Production) | -76 | -76 | -76 |
| CO2 Uptake for Year 81 to 100 (4th Production Aggregates) | | | -378 |
| CO2 Uptake for Year 81 to 100 (3rd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (1st Production Aggregates) | | | 0 |
| Total Additive CO2 after 100 years | 3234 | 3461 | 1962 |

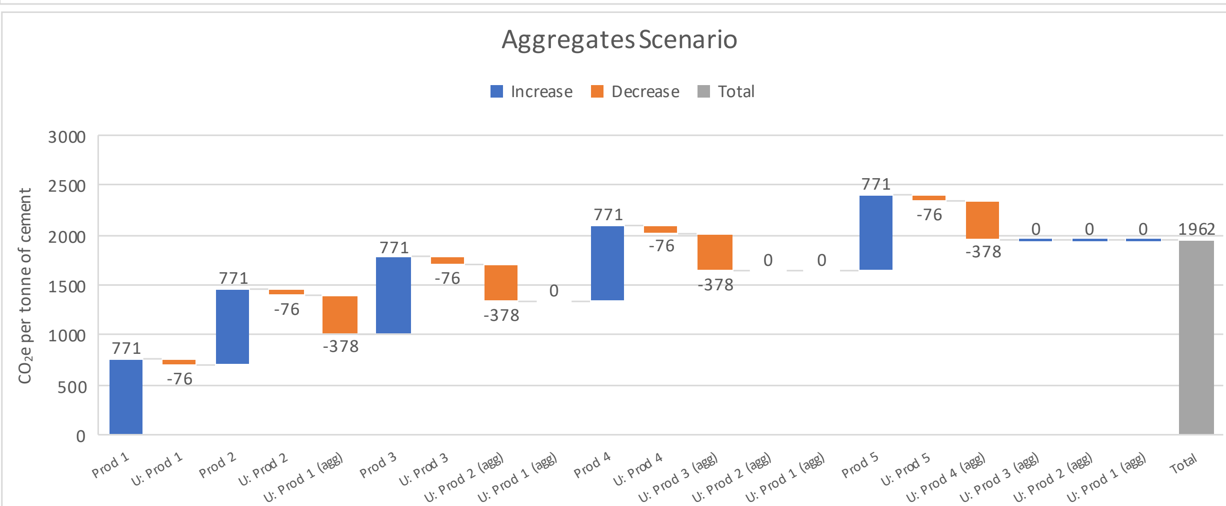
| | | | |
|---|---|---|---|
| Additive CO2 After 20 years | 694.67 | 694.67 | 694.67 |
| Additive CO2 After 40 years | 1,329.53 | 1,386.37 | 1,013.54 |
| Additive CO2 After 60 years | 1,964.39 | 2,078.06 | 1,332.40 |
| Additive CO2 After 80 years | 2,599.25 | 2,769.76 | 1,651.27 |
| Additive CO2 After 100 years | 3,234.11 | 3,461.45 | 1,970.13 |

*Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*
*Jurisdiction: Canada; Service Life: 20 years*

| Primary | Secondary | Strength |
|---|---|---|
| Exposed | Buried | <15 MPa |



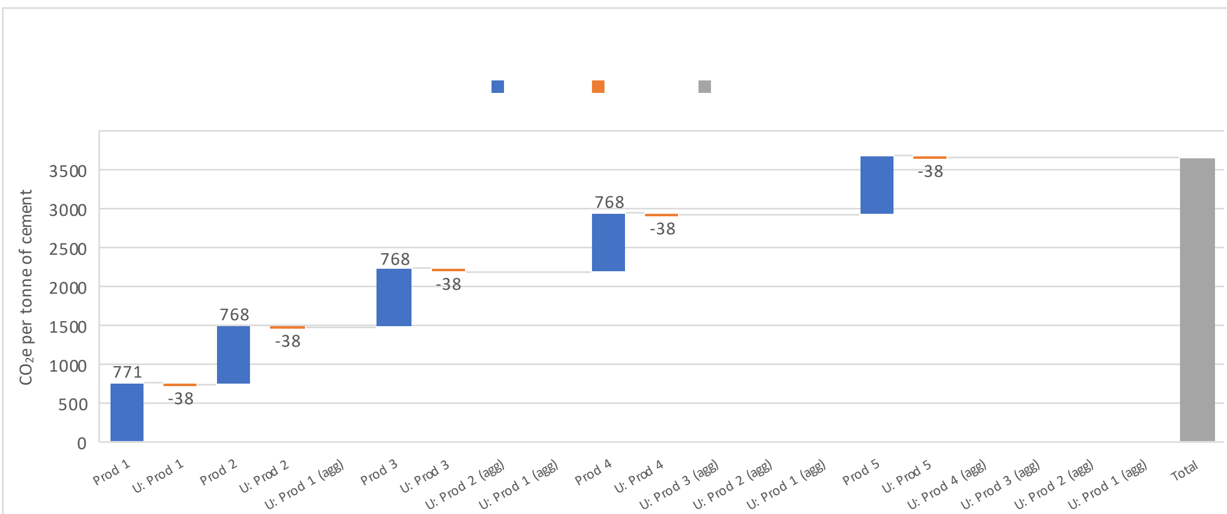



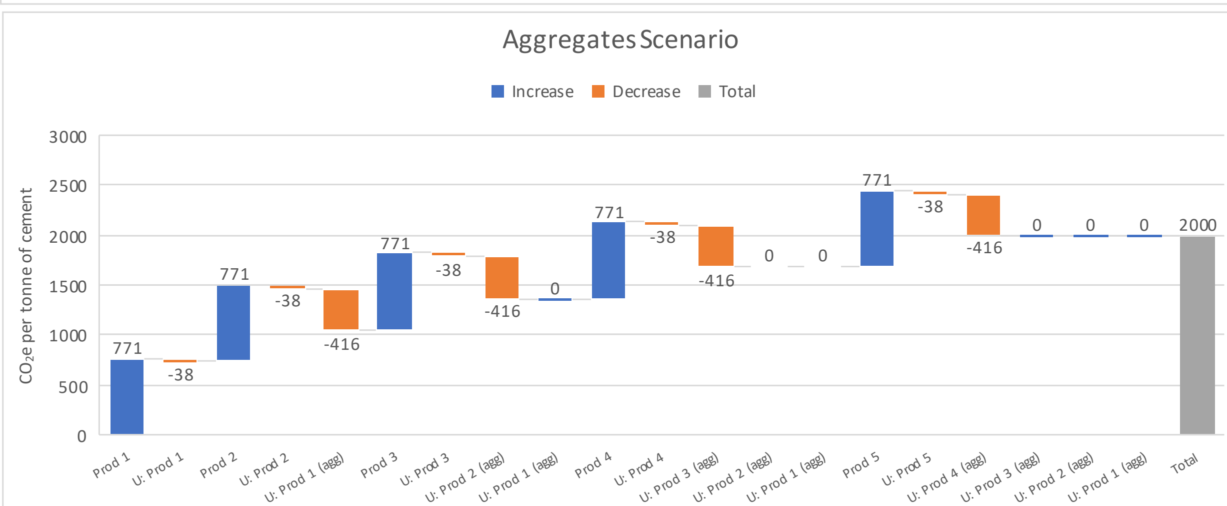
| *Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*<br>*Jurisdiction: Canada; Service Life: 20 years* | **Primary**<br>**Buried** | **Secondary**<br>**Buried** | **Strength**<br>**15-20 MPa** |
|---|---|---|---|
| **Substituion Type** | **Raw Material** | **Clinker** | **Aggregates** |
| 1st Production | 771 | 771 | 771 |
| CO2 Uptake Year 0 to 20 | -38 | -38 | -38 |
| 2nd Production | 705 | 768 | 771 |
| CO2 Uptake for Year 21 to 40 (2nd Production) | -38 | -38 | -38 |
| CO2 Uptake for Year 21 to 40 (1st Production Aggregates) | | | -416 |
| 3rd Production | 705 | 768 | 771 |
| CO2 Uptake for Year 41 to 60 (3rd Production) | -38 | -38 | -38 |
| CO2 Uptake for Year 41 to 60 (2nd Production Aggregates) | | | -416 |
| CO2 Uptake for Year 41 to 60 (1st Production Aggregates) | | | 0 |
| 4th Production | 705 | 768 | 771 |
| CO2 Uptake for Year 61 to 80 (4th Production) | -38 | -38 | -38 |
| CO2 Uptake for Year 61 to 80 (3rd Production Aggregates) | | | -416 |
| CO2 Uptake for Year 61 to 80 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 61 to 80 (1st Production Aggregates) | | | 0 |
| 5th Production | 705 | 768 | 771 |
| CO2 Uptake for Year 81 to 100 (4th Production) | -38 | -38 | -38 |
| CO2 Uptake for Year 81 to 100 (4th Production Aggregates) | | | -416 |
| CO2 Uptake for Year 81 to 100 (3rd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (1st Production Aggregates) | | | 0 |
| Total Additive CO2 after 100 years | 3402 | 3650 | 2000 |

| | | | |
|---|---|---|---|
| Additive CO2 After 20 years | 732.74 | 732.74 | 732.74 |
| Additive CO2 After 40 years | 1,399.95 | 1,462.17 | 1,051.61 |
| Additive CO2 After 60 years | 2,067.15 | 2,191.61 | 1,370.47 |
| Additive CO2 After 80 years | 2,734.36 | 2,921.04 | 1,689.34 |
| Additive CO2 After 100 years | 3,401.56 | 3,650.47 | 2,008.20 |

*Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*
*Jurisdiction: Canada; Service Life: 20 years*

| Primary | Secondary | Strength |
|---|---|---|
| Buried | Buried | 15-20 MPa |



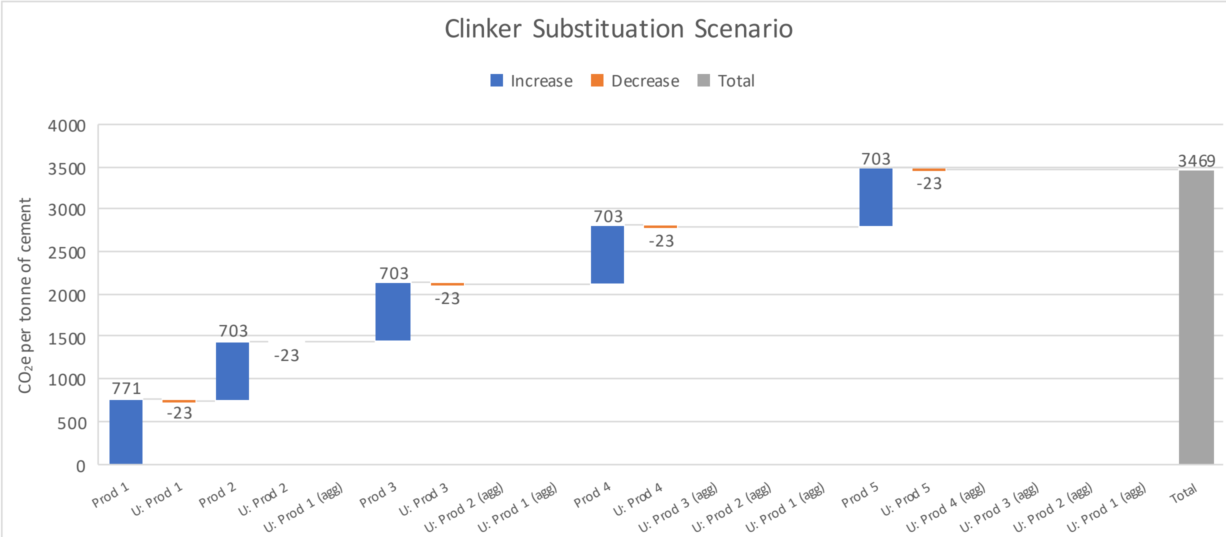



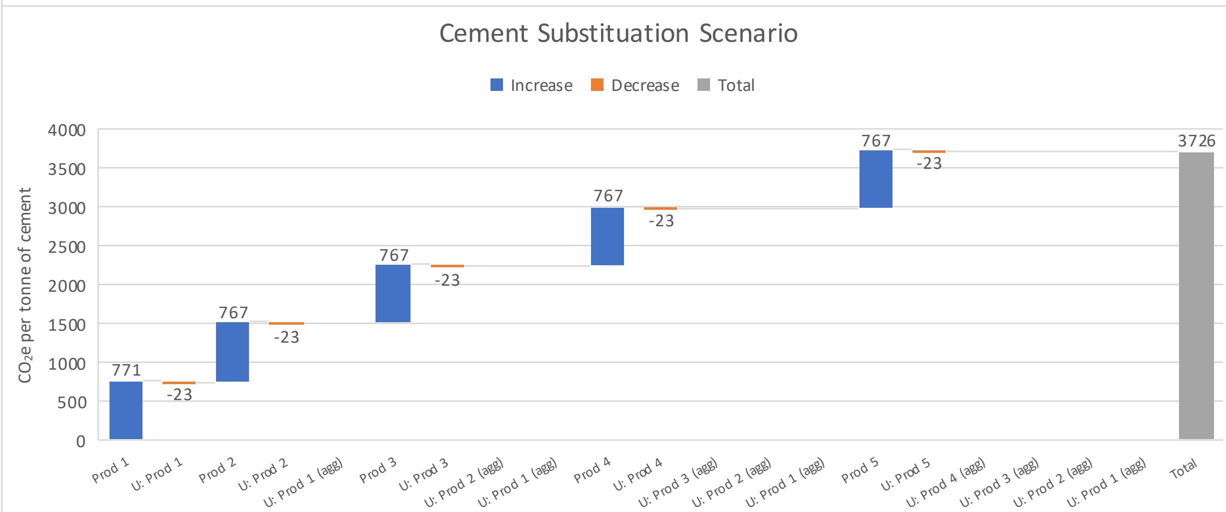
| *Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm<br>Jurisdiction: Canada; Service Life: 20 years* | **Primary**<br>**Exposed** | **Secondary**<br>**Buried** | **Strength**<br>**25-30 MPa** |
|---|---|---|---|
| **Substituion Type** | **Raw Material** | **Clinker** | **Aggregates** |
| 1st Production | 771 | 771 | 771 |
| CO2 Uptake Year 0 to 20 | -23 | -23 | -23 |
| 2nd Production | 703 | 767 | 771 |
| CO2 Uptake for Year 21 to 40 (2nd Production) | -23 | -23 | -23 |
| CO2 Uptake for Year 21 to 40 (1st Production Aggregates) | | | -399 |
| 3rd Production | 703 | 767 | 771 |
| CO2 Uptake for Year 41 to 60 (3rd Production) | -23 | -23 | -23 |
| CO2 Uptake for Year 41 to 60 (2nd Production Aggregates) | | | -399 |
| CO2 Uptake for Year 41 to 60 (1st Production Aggregates) | | | -32 |
| 4th Production | 703 | 767 | 771 |
| CO2 Uptake for Year 61 to 80 (4th Production) | -23 | -23 | -23 |
| CO2 Uptake for Year 61 to 80 (3rd Production Aggregates) | | | -399 |
| CO2 Uptake for Year 61 to 80 (2nd Production Aggregates) | | | -32 |
| CO2 Uptake for Year 61 to 80 (1st Production Aggregates) | | | 0 |
| 5th Production | 703 | 767 | 771 |
| CO2 Uptake for Year 81 to 100 (4th Production) | -23 | -23 | -23 |
| CO2 Uptake for Year 81 to 100 (4th Production Aggregates) | | | -399 |
| CO2 Uptake for Year 81 to 100 (3rd Production Aggregates) | | | -32 |
| CO2 Uptake for Year 81 to 100 (2nd Production Aggregates) | | | 0 |
| CO2 Uptake for Year 81 to 100 (1st Production Aggregates) | | | 0 |
| Total Additive CO2 after 100 years | 3469 | 3726 | 2047 |

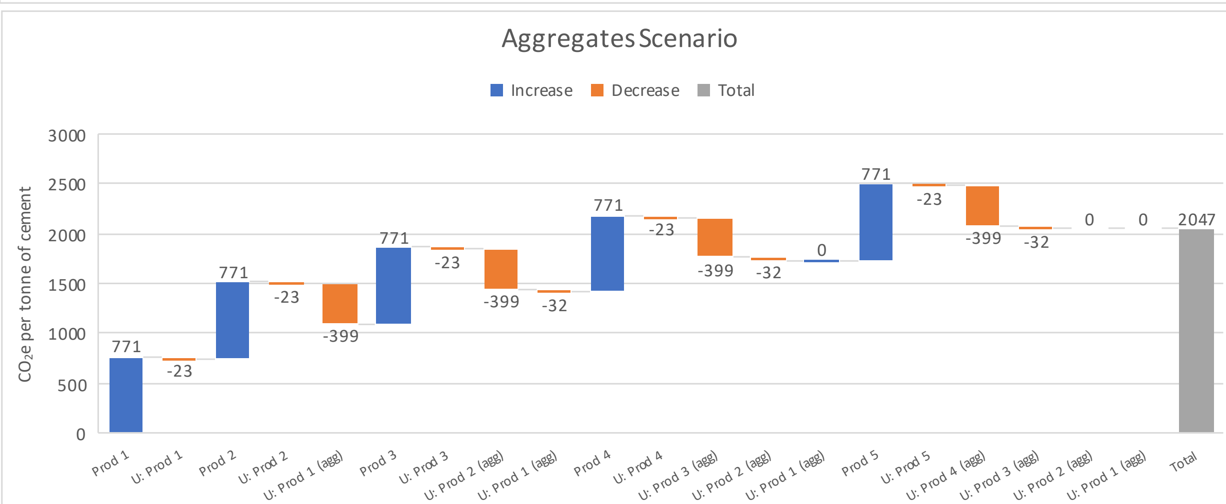
| | | | |
|---|---|---|---|
| Additive CO2 After 20 years | 747.97 | 747.97 | 747.97 |
| Additive CO2 After 40 years | 1,428.13 | 1,492.50 | 1,099.03 |
| Additive CO2 After 60 years | 2,108.28 | 2,237.02 | 1,417.89 |
| Additive CO2 After 80 years | 2,788.44 | 2,981.55 | 1,736.76 |
| Additive CO2 After 100 years | 3,468.60 | 3,726.08 | 2,055.62 |

*Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*
*Jurisdiction: Canada; Service Life: 20 years*

| Primary | Secondary | Strength |
|---|---|---|
| Exposed | Buried | 25-30 MPa |



| *Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm Jurisdiction: Canada; Service Life: 20 years* | **Primary Exposed** | **Secondary Buried** | **Strength > 35 MPa** |
|---|---|---|---|
| **Substituion Type** | **Raw Material** | **Clinker** | **Aggregates** |
| 1st Production | 771 | 771 | 771 |
| CO2 Uptake Year 0 to 20 | -15 | -15 | -15 |
| 2nd Production | 702 | 767 | 771 |
| CO2 Uptake for Year 21 to 40 (2nd Production) | -15 | -15 | -15 |
| CO2 Uptake for Year 21 to 40 (1st Production Aggregates) | | | -299 |
| 3rd Production | 702 | 767 | 771 |
| CO2 Uptake for Year 41 to 60 (3rd Production) | -15 | -15 | -15 |
| CO2 Uptake for Year 41 to 60 (2nd Production Aggregates) | | | -299 |
| CO2 Uptake for Year 41 to 60 (1st Production Aggregates) | | | -126 |
| 4th Production | 702 | 767 | 771 |
| CO2 Uptake for Year 61 to 80 (4th Production) | -15 | -15 | -15 |
| CO2 Uptake for Year 61 to 80 (3rd Production Aggregates) | | | -299 |
| CO2 Uptake for Year 61 to 80 (2nd Production Aggregates) | | | -126 |
| CO2 Uptake for Year 61 to 80 (1st Production Aggregates) | | | -14 |
| 5th Production | 702 | 767 | 771 |
| CO2 Uptake for Year 81 to 100 (4th Production) | -15 | -15 | -15 |
| CO2 Uptake for Year 81 to 100 (4th Production Aggregates) | | | -299 |
| CO2 Uptake for Year 81 to 100 (3rd Production Aggregates) | | | -126 |
| CO2 Uptake for Year 81 to 100 (2nd Production Aggregates) | | | -14 |
| CO2 Uptake for Year 81 to 100 (1st Production Aggregates) | | | 0 |
| Total Additive CO2 after 100 years | 3502 | 3764 | 2176 |

| | | | |
|---|---|---|---|
| Additive CO2 After 20 years | 755.58 | 755.58 | 755.58 |
| Additive CO2 After 40 years | 1,442.22 | 1,507.66 | 1,214.00 |
| Additive CO2 After 60 years | 2,128.86 | 2,259.73 | 1,546.80 |
| Additive CO2 After 80 years | 2,815.49 | 3,011.80 | 1,865.66 |
| Additive CO2 After 100 years | 3,502.13 | 3,763.88 | 2,184.53 |

*Concrete thickness: 250 mm; Aggregate Size for EOL use: 22.4 mm*
*Jurisdiction: Canada; Service Life: 20 years*

| | | |
|---|---|---|
| **Primary** | **Secondary** | **Strength** |
| **Exposed** | **Buried** | **> 35 MPa** |