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Building a User-Friendly LCI Prediction Model for Concrete Mixtures

Harnish Sharma[1], Anthony Torres[1,*], Yoo Jae Kim[1], Jiong Hu[2], Vedaraman Sriraman[1] and Jake Ellis[1]

[1]*Texas State University, 601 University Dr., San Marcos, TX, 78666, United States*
[2]*University of Nebraska-Lincoln, The Peter Kiewit Institute, Omaha, NE 68182, United States*

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Abstract

Concrete is the corner stone of the construction industry and the second largest material being used after water. The growth of the construction industry and an increasing awareness of the environmental impact of human activity has accelerated the development of environment friendly solutions in concrete production and construction. Through the production of concrete and its constituents, varying amounts of CO2 are emitted into the atmosphere. In this study, a user-friendly Life Cycle Impact (LCI) model for concrete was developed. The user-friendly LCI model for concrete was developed based on the literature, which can be used for a constituent comparative analysis. This study demonstrates the practicality of a user-friendly LCI model by comparing the LCI of different concrete compositions that contain Fly Ash (FA) and Recycled Concrete Aggregate (RCA). Although this study focused mainly on the environmental impact of FA and RCA, the model was designed to analyze the impact of any conventional concrete mixture and a mixture with any combination of added or replaced constituents. The major benefit of the developed user-friendly LCI model is that it is a simple model that can be used by practically anyone in the concrete construction industry to assess and evaluate the impact of any concrete mixtures. Providing the industry with a user-friendly model that requires little time can drastically benefit practitioners in better access to environment impact of different concrete mixtures.

Keywords: CO_2 emissions, Portland cement concrete, Fly ash, Recycled Concrete Aggregate, Service life.

1. Introduction

On a global scale, concrete is by far the most widely-used and widely-produced construction material. Concrete is so integral to the continued development and growth of global infrastructure and economy that an estimated 1 tonne (3.8 tons) of concrete is consumed per person per annum worldwide (Flower and Sanjayan, 2007). Simply put, concrete is a superior, versatile, and cost-efficient building material used in countless high and low-volume applications. The prevalence of concrete construction continues to grow, so too does the potential and capability of concrete to provide innovative solutions in new and exciting applications in a countless number of global industries. However, due to its sheer volume, the concrete production and construction industry is a leading

* Corresponding author.
E-mail address: ast36@txstate.edu (Torres A.)

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contributor toward a number of environmental impacts. Due to the mass production of concrete it has become imperative to determine the environmental impact caused by the production of cement and concrete and find ways to ameliorate the deleterious impacts. Even though, in terms of per mass allocation, concrete production is far more impact-efficient in a number of categories compared to other widely-used building materials (Schwab, 2014) the scale of production and consumption makes concrete the most energy-consuming sector in the world. This makes concrete a leading contributor to impacts in other environmental categories such as pollutant releases and construction wastes. For example, the cement industry alone presently accounts for between 5 and 7 percent of anthropogenic CO2 generated worldwide (Van den Heede and De Belie, 2012). This percentage estimate should increase when the impacts from other constituent ingredients and concrete use and construction are accounted for.

Although the negative environmental impacts associated with such a critical pillar of the world economy are troubling, the situation presents a major opportunity within the concrete industry to make a major impact in the global reduction of negative environmental impact, perhaps in a manner that may save both producers and consumers of concrete materials costs. Due to the widespread and growing use of concrete worldwide, adoption of even minor eco-friendly process improvements can have far-reaching positive environmental impacts throughout the many industries that make use of concrete products (Benhelal et al., 2013). To understand how to best take advantages of opportunities to minimize environmental impact, producers and consumers of concrete are increasingly turning toward life-cycle analysis (LCA) as a tool to gain a more holistic understanding of the environmental impact of concrete products.

The following is a definition of LCA from the U.S. Environmental Protection Agency (EPA, 2006): “LCA is a “cradle-to-grave” approach for assessing industrial systems. LCA evaluates all stages of a product’s life from the perspective that they are interdependent, meaning that one operation leads to the next. LCA enables the estimation of the cumulative environmental impacts resulting from all stages in the product life cycle, often including impacts not considered in more traditional analyses (e.g., raw material extraction, material transportation, ultimate product disposal, etc.). By including the impacts throughout the product life cycle, LCA provides a comprehensive view of the environmental aspects of the product or process and a more accurate picture of the true environmental trade-offs in product and process selection (EPA 2006). Figure 1 illustrates the LCA process:

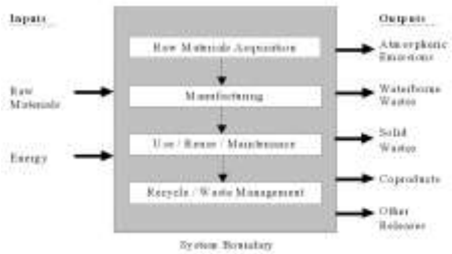

Figure 1: Illustration of the LCA process. (EPA, 1993)

In the concrete industry as described earlier, LCA helps producers of concrete to assess environmental impact beyond the direct impact of cement and concrete plant emissions – impacts embedded in raw materials, production of secondary products, transportation, use, and disposal must also be considered, among other things, to understand the full picture of environmental impact. The advantage that the LCA perspective gives concrete producers the opportunity to improve the environmental friendliness of concrete products not only at the plant, but also through new avenues on the supply side and downstream.

LCA requires extensive data collection throughout the process chain and later in the product life cycle, which presents a significant resource barrier for companies seeking to incorporate LCA into their environmental research. Nonetheless, smaller companies lacking the resources for the large-scale environmental data collection and experimental analysis, yet required to make LCA-based environmental improvements may have many advantages to gain in reducing the environmental impact of their products. Recently, several researchers have developed predictive LCA models that obviates the difficulties (such as extensive and reliable data required) associated with conducting an extensive LCA and makes it relatively easily to evaluate environmental impacts (*DeVierno et al. 2012*). The following presents prior research in the use of predictive modeling in evaluating environmental impacts.

The large amounts of data that are difficult to collect in practice makes LCA studies expensive and time consuming (*Pascual-Gonzalez et al., 2015*). To overcome this difficulty, researchers from different disciplines in the science and engineering community have developed various predictive methods that incorporate data from prior, well-established studies (*Pascual-Gonzalez et al., 2015*). Past research has employed a mix of methods such as multivariate regression analysis, clustering methods and artificial neural networks (ANNs) (*Park and Seo, 2003*). Park and Seo (2003) used an approach that combined ANNs and regression analysis. They began by using clustering methods to form groups of similar products from amongst a larger set of dissimilar products. Product attributes were then mapped into environmental impact driver indices. ANNs were then used to predict impacts from environmental impact drivers.

Wang et al. (2010) used multivariate regression analysis to establish the relationship between several predictor variables and a criterion variable in context of using iterative data to achieve a more accurate picture of environmental impacts. Given that there is uncertainty in the knowledge of input factors of a LCA, the researchers used multivariate regression analysis to conduct uncertainty and sensitivity analysis. DeVierno et al. (2012) used linear regression analysis to establish the relationship between product design variables and their environmental impact in the instance of mechanical design. Their objective was to validate design changes by their impact on product environmental impact. Regression analysis was used in streamlined LCA of homogeneous sets of products using proxy indicators. Proxy indicators are environmental impacts that are easy to establish and are used in place of full-scale LCA results (*Hanes et al. 2013*). In the area of advanced biofuels and their impact on greenhouse gas (GHG) emissions, Menten et al. (2013), address the issue of high variability in the results from different LCA studies. They used meta regression analysis (multivariate statistical analysis of previously estimated results) to synthesize available information and to improve understanding of the main factors inducing GHG emission variations. A combination of multiple linear regression and mixed integer programming was used by Pascual-Gonzalez et al., (2015) to construct impact models that predict the impact in different environmental impact categories based on a reduced number of proxy indicators.

The foregoing research suggests that predictive modeling of environmental impact based on LCA research presents a potential resource-effective solution in estimating life-cycle impact that can be used effectively in many situations. Compiling available LCA case studies into a predictive model via regression analysis can be used to estimate the impact of new concrete construction, and to compare and assess the potentially impact-reducing effects of environmentally-friendly materials and techniques before construction takes place (*Boeschet al. 2009*). However, these “user-friendly” LCA techniques that utilize multivariate regression techniques may be a simple method for an academician, but it is not very simple for a broad audience such as construction personnel, designers, and even consumers. Therefore, a more user-friendly model that a broader audience can use is needed. In general, a LCA may be too broad to be user-friendly, in which a Life Cycle Impact (LCI) may be better suited for a broader audience as an LCI directly focuses on the impact of the material/process investigated.

In this study, a user-friendly LCI analysis is developed and analyzed that can be used by virtually anyone. This study inventories most of the commonly used constituents to produce concrete and their individual environmental (CO_2 emissions) impact are quantified such that a simple input-output LCI can be produced. The model is constructed in such a way that any conventional concrete can be investigated and any modifications to the mixture can also be investigated, such as incorporated recycled materials. The impact of each constituent was determined from readily available and validated sources. Constructing a simple impact model based on inputs that are readily available to any consumer of concrete allows for impact estimation and analysis to be conducted by anyone involved in the concrete life-cycle, including consumers. Lastly, input-output modeling provides other opportunities for optimization in concrete mixtures and process/construction design, which can also benefit the industry.

2. Input Parameters and Existing Models

A fact-based study to estimate environmental impact of concrete is only possible through LCA/LCI of concrete *(Marceau et al., 2006; Gursel et al., 2014; Van den Heede and De Belie, 2012).* Therefore, it is not possible to measure the environmental impact of concrete without considering constituents or input of the concrete composition. The input parameters of the developed model are the individual concrete constituent's contribution to CO_2 emissions. To better understand this, background information is provided for manufacturing process of each concrete constituent. Additional information is provided as to how the constituents are batched together to produce a concrete mixture. The developed model will also consider the addition of recycled material to replace certain constituents, service life of the concrete, and the transportation of the constituents and mixed concrete to the construction site. As Purnell and Black (2012) state in their study, the equivalent CO_2 emissions with known mixture constituents can be estimated using the emissions contributions from the constituents of concrete.

2.1. Concrete constituent manufacturing process

Concrete is an important construction material; however it causes some environmental impacts (*Flower and Sanjayan, 2007; Kim et al., 2013; Purnell & Black et al., 2012; Benhelal et al., 2013; and Gursel et al., 2014*). Concrete is a composite material consisting of Portland cement, water, fine aggregate (sand), coarse aggregate (rock/stone), and sometimes chemical admixtures and supplemental cementitious materials (SCMs). The Portland cement reacts with the water to create a liquid binder that holds together aggregate materials. Once the liquid concrete cures (hardens) strength is gained, such that the resulting material can be used as a building material. As previously mentioned, other chemical admixtures can be used to alter desired properties of the material. Additionally, varying the mass of each constituent permit alteration on the desired properties of the material. SCMs are a type of material that provides additional cementitious value to the mixture, which also can be used to alter the properties of the mixture and often replace a percentage of the Portland cement used. All of these constituents are each manufactured separately and brought together at the construction site or at a local batching plant, in which they are proportioned and mixed. In order to develop an accurate LCI and LCA of concrete, each major constituent needs to be assessed.

2.1.1. Portland Cement Production

Portland cement is by far the most widely-used and cost-effective concrete binder material. This highly caustic hydraulic cement consists primarily of calcium silicates, which has been in use for centuries. Portland cement is made through pyroprocessing in a rotary kiln, where calcium carbonate reacts with silica-bearing materials at high temperatures in a calcination process. The majority of the CO_2 emissions are produced during the calcination process ($CaCO_3 \rightarrow CaO + CO_2$) (*Marceau, et al, 2006*). Materials are sintered into a solid clinker at high temperatures (~3000ºF), and the clinker is ground finely to make cement. The high temperatures at which Portland cement is formed as well as the raw materials and clinkers grinding processes make cement production a highly energy-intensive process, resulting in large amounts of direct and indirect CO_2 emissions. Approximately 800g of CO_2 are produced in the production of 1 kg of cement (Josa et al., 2007). Furthermore, pyroprocessing also releases atmospheric SO_2 and NO_x emissions in significant amounts, as well as generating a large amount of harmful kiln dust (*Marceau, et al, 2006*).

2.1.2. Natural fine/coarse aggregates

Concrete aggregates can be derived from a variety of natural stone sources, including stone quarries and riverbed gravel. Fine aggregate generally consists of sand, whereas coarse aggregate must usually be crushed to an appropriate size for inclusion in concrete. Due to their weight, aggregates are incredibly costly to transport long distances, with transportation costs in some cases doubling every 30 km (*Marinković et al., 2010*). As such, concrete aggregates are generally sourced at very short distances using locally-available stone sources and transported via efficient methods such as road, barge and rail transport.

2.1.3. Fly Ash/Bottom Ash (FA)

FA is a fine powder formed as a waste product during the combustion of coal for electricity generation. FA is a pozzolanic material, meaning that it reacts with calcium hydroxide in the presence of water at normal temperatures to gain cementitious properties. Bottom ash is simply an agglomeration of FA particles, and can be ground to have the same cementitious properties as cement *(O'Brian et al., 2009)* and can be used as SCMs.

2.1.4. Recycled Concrete Aggregate (RCA)

Construction and demolition (C&D) waste of concrete structures is the major localized source of impact if concrete is not properly recycled. To avoid spent concrete wastefully occupying landfill space, concrete structures can be demolished, stripped of reinforcement, and crushed into aggregate, which can then be used in many construction and landscaping applications. RCA, once properly cleaned of all metals and organic compounds, can be re-used as aggregate in fresh concrete, thereby avoiding major source of waste. However, the process of deconstructing, crushing, cleaning, and transporting RCA is incredibly energy-intensive, contributing to global impact factors such as GHG emissions at a higher rate than virgin aggregate. Immediate benefits of RCA usage are not reflected in the global impact constraints but it has the potential to conserve natural gravel resources and limit waste streams to landfills *(Knoeri et al., 2013).*

2.1.5. Concrete Service Life

Although the service life is not a specific constituent of concrete, service life is discussed here as this is a key variable in determining the LCI and LCA of concrete. Service life differs from the other environmental impact factors discussed above as it is not an adjustable independent variable in concrete mix design – service life is dependent on an uncountable number of major and minor factors that affect the durability of the concrete structure, from materials to mix design, geometry, environmental factors, and so much more. However, service life is perhaps the most important factor determining the LCI of concrete, as a longer service life can make other impact factors insignificant in the long run. Although much of the research in LCA-based improvement of concrete involves reducing the impact costs of concrete production (cradle-to-gate), a full cradle-to-grave perspective of LCA reveals opportunities to focus on improving the mechanical and durability properties of concrete as an equally-effective method of reducing LCI.

2.1.6. Transportation

For the scope of the user-friendly LCI model developed in this study, the transportation impact will include transportation of aggregate to the concrete plant, and the transportation of mixed concrete via a concrete truck to the job site. Depending on the sourcing distances and available materials, concrete mix ingredients can be transported by truck, ship, or rail *(Sujunnesson, 2005).* As such it is important to determine how concrete material are being sourced in order to assess the environmental impact of transportation for any specific local application. To accurately estimate the transportation impact for a specific local application, the most critical factor is the distance that the concrete mix must travel before being poured at the job site.

This study is limited in scope to match the boundaries set by concrete's constituent elements. Only global warming potential can be readily translated between LCA case studies: many "local" environmental impacts such as landfills usage or construction waste are too subjected to geographically-specific or application specific factors that limit their applicability towards a global impact model. Output models are constructed for the GHG emissions in Carbon Dioxide mass equivalent (CO_2e) – a primary industrial emission resulting from the burning of fossil fuels and direct contributor to global warming. There are limited reports on the specific environmental impact of transportation and how it relates directly to a unit length of measurement (i.e. distance traveled) as the varying transportation methods output varying degrees of emissions due to weight of load and vehicle, type of engine, type of fuel, traffic and road conditions, and driving efficiency of the operator, etc. The few reports that quantified transportation provided insight into general transportation distance of approximately 80.46 km (50 mile) radius (*Sujunnesson, 2005).* Most concrete producers position themselves within 50 miles of their material providers to minimize transportation cost. This also translates to the customer. A contractor ordering concrete will almost always order from the nearest concrete producer, which is often within an 80.46 km (50 mile) radius (*Sujunnesson, 2005).* Therefore the transportation values used for this analysis will assume a maximum of 80.46 km (50 mile) transportation distance.

2.2. Existing Models

Flower and Sanjayan (2007) studied and provided hard data collected from a number of quarries and concrete manufacturing plants so that an accurate estimate can be made for concrete for use in developing environmentally sustainable design (ESD). Among various environmental effects, green house emissions are a major concern (*Huntzinger et al., 2007; Gursel et al., 2014; Benhelal et al., 2012)*. Concrete mix design corresponding to the environmental cost and performance counter balance the societal demands in terms of environment and technical building requirements (Habert, G & Roussel, N., 2009). CO_2 e rises with the increase in concrete strength due to cement content this can be reduces with the replacement of cement with FA, crushed aggregate, superplasticizer, and high strength cement and achieving optimum strength (*Purnell, P & Black, L., 2012).*

There are multiple studies present which compares the Life Cycle Impact Assessment (LCIA) of different life cycle inventories for cement *(Flower and Sanjayan, 2007; Kim et al., 2013; O'Brian, K.R et al., 2009)*. CO_2 emissions of concrete are not a simple function of strength it can be reduced by conscientious attention to the mix design (Kate et al., 2007). As a result many studies were conducted to substitute cement in concrete to reduce CO_2 emissions *(Van den Heede and De Belie, 2012; Marinkovic et al., 2010; Benhelal et al., 2012).* The most common replacements are post-industrial waste such as Fly Ash (FA). Multiple studies have been completed on substituting cement with FA and other byproducts *(Berndt, 2009; Chen et al., 2010; and Kim et al., 2013).* FA was found capable of reducing concrete CO_2 emissions by 13% to 15% in typical concrete mixtures (*Flower and Sanjayan, 2007).*

Van den Heede and De Belie, 2012 interpreted in their case study that when applying a mass allocation of impacts for FA, practically all categories indicate values exceed their corresponding values for the Portland cement. They also concluded that the environmental benefits of using FA are only produced when the economical allocation principle is adopted. It is also stated in their literature interpretation that the impacts of FA are higher than using other byproducts such as slag from steel production. It is attributed to very little FA (0.052 kg) produced per kWh of electricity, while a lot more slag is produced per kg of steel (0.24 kg). Therefore, constituents of concrete have varying impacts on environmental via CO_2 emissions *(Kim et al., 2013; Huntzinger et al., 2009; and Gartner 2004).* It is rather easy to change concrete mix design, however there are no tools or models to measure constituents in their overall impact on CO_2.

Environmental impact of concrete production depends on the binder content (i.e. cement, FA, blast furnace slag etc.) and transportation required *Schepper et al., 2014* concluded the reduction of 30%- 34% GWP with replacement of FA and Blast Furnace Slag in their study. They found that with the design of concrete mix of high strength RCA with low clinker content there is a reduction of about 66%-70% in GWP.

O'Brian, et al (2009) developed an equation to predict embodied emissions in concrete as a function of FA content and total mass of cementitious material, which assists in formulating concrete to meet specific emissions targets. Their study shows that irrespective of the FA transportation distance it can still deliver a net saving in Green House Gas (GHG) emissions if used to replace Portland cement in concrete. Water consumption accounts for more than 89% of water embodied in concrete, FA content has negligible effect on embodied water.

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3. Methods

3.1. Scope of Study

The goal of this study is to develop a user-friendly LCI model of Portland cement concrete by analysis of present LCA case studies. Comparing the LCI of different concrete compositions with varying SCMs will help to estimate the environmental impact of these compositions. A user-friendly LCI model will allow users to compare the impact of various concrete mixtures to that of mixtures containing SCMs or RCA. The model is simple so it can be conveniently used to benefit the construction industry, concrete producers and consumers. The research model is constructed based on the data available from current peer reviewed LCA research and case studies. Data for the regression coefficients are taken from these studies are therefore assumed to be valid. The model is only designed to validate the environmental impact (GHG emission) of various concrete mixtures, therefore, possible higher order (interactions) between constituents and their effect on other performance criteria are not considered. The study is aligned with creating a concrete model with high applicability for the industry. However, the environmental impacts associated with construction and in-service maintenance are omitted for the purpose of this study. The model is constructed for reporting impact in terms of GHG emissions in carbon dioxide mass equivalents (CO_{2e}).

3.2. Life Cycle Inventory and Functional unit

3.2.1. Life Cycle Inventory

The life cycle inventory is a part of the LCA, a technique accounting for the environmental loads during the product's life cycle. The purpose of this step involves data collection of environmental impact and quantifying inputs and outputs of the system. In this study, GHG emissions in CO_{2e} are considered and an analysis of LCA with traditional concrete with sustainable alternatives has been completed. Carbon dioxide is the major GHG released during the production of cement used in concrete. This type of LCI analysis will provide an aide to the construction industry to predict the environmental impact of new construction by comparison of the designed concrete mixture.

In developing the user-friendly LCI model, the model will be tested using a conventional concrete mixture used as a control, which will be compared to a modified conventional concrete mixture that uses either FA as partial replacement of the Portland cement or RCA as partial replacement to the natural coarse aggregate. In order to run these cases, the per weight impact for each raw material (Portland cement, natural coarse and fine aggregate, FA, and RCA) need to be obtained. This was done through an exhaustive and comprehensive peer reviewed published literature survey. A minimum of three data points, from three difference sources, were collected or back calculated and reported in Table 1. Table 2 shows the final averaged values used in the model.

Table 1: Impact model coefficients sources.

Impact Factor	**Emission to Air (Kg CO_2e/Kg)**	**Source**
Portland Cement	0.82	Flower et al. (2007)
Portland Cement	0.79	O'Brian et al. (2009)
Portland Cement	0.8612	Marinkovics et al. (2010)
Portland Cement	0.913	Fact Sheet UK
Portland Cement	0.82	Collins (2010)
Portland Cement	0.918	A.Josa et al.
Portland Cement	0.83	Prunell et.al (2012)
Fly Ash	0.027	Flower et al. (2007)
Fly Ash	0.01	P.E International (2011)
Fly Ash	0.01	Prunell et.al (2012)
Coarse Aggregate	0.0032	Zapata and Gambatese (2005)
Coarse Aggregate	0.005	Prunell et al. (2012)
Coarse Aggregate	0.001379	Marinkovic.s et al. (2010)

Recycled coarse Aggregate	0.001695	Marinkovic.s et al. (2010)
Recycled Coarse Aggregate	0.001589	Knperi et al. (2013)
Recycled Coarse Aggregate	0.001601	Prunell et al. (2012)
Fine Aggregate	0.00185	Knperi et al.(2013)
Fine Aggregate	0.001379	Marinkovic.s et al. (2010)
Fine Aggregate	0.0032	Zapata and Gambatese (2005)
Transportation	1.917×10^{-5}	Sjunnesson (2005)
Transportation	1.6×10^{-5}	Prunell et.al (2012)
Transportation	1.89×10^{-5}	Flower et al. (2007)

Table 2: Impact Factor Coefficients.

Coefficient	**Impact Factor**	**Per-Weight Impact (Kg CO_2e/Kg)**
α_1	Portland Cement	0.8327
α_2	Fly Ash	0.01567
β_1	Coarse Aggregate	0.003193
β_2	Recycled Coarse aggregate	0.00165
γ	Fine Aggregate	0.002143
$\mathbf{T}_r$	Transportation	0.000176

All values for each constituent were within the range of 10% to 12% of each other and any value that was over 15% difference from the other sources was investigated further and were ultimately not considered as it was considered an outlier due to the large disparity and other factors that were not consistent with other reports including other variables not relevant the specific impact of the constituent, source dated, or other limiting factors. Life cycle of the concrete starts from the extraction to the production of the raw materials (i.e. extracting and processing natural aggregate in the quarry, water exploitation and the production of the cement at the cement plant) and ending with recycling of concrete. Transportation of the materials to the concrete batching plant and then concrete mix to the construction site is involved. System includes fly ash as inputs including their transportation, also fly ash does not need any special treatment before it is replaced partially for cement. (Van den Heede and De Belie, 2012). Construction, Service phase and demolition phase are excluded.

Figure 2 depicts the system that was considered and the source of GHG emissions during production and transport. In this system a power station provides both power and fly ahs to the production of concrete. The concrete production output is concrete to the construction site and the construction site provides demolition for RCA that then returns to concrete production. Other factors that feed into concrete production is the production of aggregate and cement.

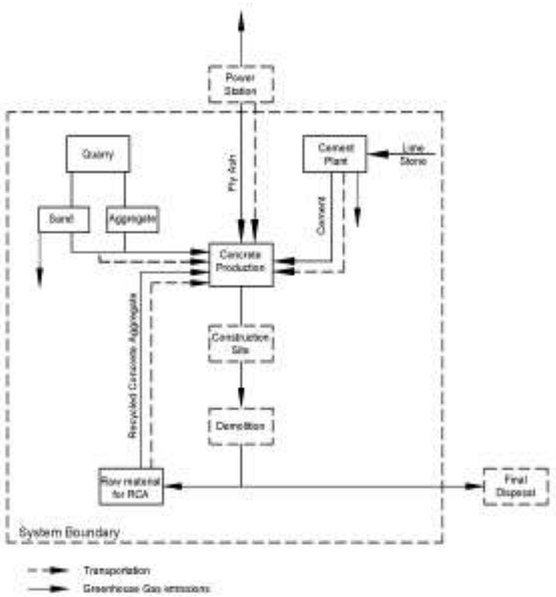

Figure 2: Flow chart of life cycle inventory of concrete constituents.

3.2.2. Functional Unit

The functional unit represented in the impact model is one paved highway mile with a width of 7.315m (24-ft) and thickness of 0.2286m (9-in) – equivalent to approximately 2,691m^3 (95,032 ft^3) in total. Assuming a concrete density ρ = 2400kg/m^3 (150 lb/ft^3), the model functional unit weighs 6.458E6 kg (6458 tons). As the replacement level of alternative cementitious and aggregate materials in the model is adjusted, it is assumed that in all cases, a constant per-weight concrete mix ratio consisting of 1 part-369.23 kg/m^3 (23.05 lb/ft^3) cementitious material, 2 parts- 738.46 kg/m^3 (46.10 lb/ft^3) dry fine aggregate, 3 parts- 1,107.69 kg/m^3 (69.15 lb/ft^3) dry coarse aggregate, and ½ part water 184.61 kg/m^3 (11.52 lb/ft^3). When mixed with 100 percent Portland cement and virgin rock aggregate, this mixture produces a concrete with a compressive strength of around 40MPa, *(Sjunnesson, 2005)* which is consistent with U.S. Federal Highway Administration (FHA) guidelines on concrete pavements (*U.S. Federal Highway Administration, 2014*). In this analysis, the following are investigated: FA as an alternative supplemental cementitious material in addition to Portland cement and RCA as a substitute to the virgin coarse aggregate.

3.2.3. Model Design

A user-friendly approach was developed such that the LCI for a functional unit of concrete can be demonstrated as:

Impact = (Cementitious material production impact + Aggregate production impact +Transportation Impact) / Service Life which can be represented as

$$I = \frac{C}{SL} \qquad \text{Eq. 1}$$

Where I represents the life-cycle impact of the concrete structure (CO_2e emission), C is the summation of the constituent material and transportation and SL is the effective service life of the concrete i.e., period during which the concrete structure will perform satisfactorily without any need for maintenance. Service life is a design value that affects the total impact of GHG emissions, as additional concrete input is not needed for longer existing structures. This value is variable from state to state and from mixture to mixture. The service life also changes with the use of recycled materials. Several state Departments of Transportation (DOTs) have set their concrete mix configuration to achieve long life concrete pavements. For example; Minnesota DOT (MNDOT) has a standard for 60 years of SL with the addition of 20%- 30% of FA or of 35% GGBFS and changes in construction details that Washington State DOT (WSDOT) use class C FA 35% by weight of total cementitious material to achieve 50 years of SL. Many U.S. highway agencies have started to design pavement of low-maintenance service life of 40 years or more. For the initial models below, the service life is taken from a historical study done by various U.S. state transportation department in which they determined an average service life of a traditional concrete mixture to be 39 years *(Van den Heede & De Belie, 2012).* From Eq. 1 the constituent impact C can be further broken down to fit the desired input of the model.

$$C = \sum_{i=1}^{n} \alpha_i m_i + \sum_{j=1}^{n} \beta_j m_j + \gamma m_k + T_r \qquad \text{Eq. 2}$$

Where m_i is the mass of each binder material, Portland cement and FA, and m_j represents the mass of natural coarse aggregate and RCA and m_k represents fine aggregate, per functional unit in the concrete mixture and α_i,β_j,γ are coefficients. These represent the GHG per-weight impact derived from the data available and an approximate density of 2,400kg/m3 (150lb/ft3), which stem from the production of binder materials, coarse aggregate and fine aggregate, respectively shown in Table 1. Finally Tr represents the impact from the transportation of the concrete constituents and the mixed concrete.

It is observed in this model that the cement and aggregate types each contribute independently to the total environmental impact. This model can yield an estimate of the LCI of concrete given the mass of each cementitious material and aggregate type. However, the exact mass of each input material is not widely available for the use by potential end-user of the model. A constant concrete density and the constant ratio of binder, aggregate, and water is assumed as a part of the functional unit, the representation of the material input can be effectively changed from individual mass to fractions of the total concrete mass, which is more useable at the input level. Modified this way, the impact for cement aggregate production are as follows:

$$C = \sum_{i=1}^{n} \alpha_i u_i R_i + \sum_{j=1}^{n} \beta_j \, v_j R_j + \gamma\delta + T_r \qquad \text{Eq. 3}$$

Where R_{ij} represents the ratio of each cement and aggregate type such that $\Sigma_{i=1}^{n} R_i = 1$ and $\Sigma_{j=1}^{m} R_j = 1$. The coefficient u_{ij}, v_{ij}, & δ are the ratio-to-mass conversion constant for binder, coarse aggregate, and fine aggregate based on the overall density of concrete and the weight ratios between binder, aggregate, and water determined in the pavement functional unit. The values of ratio-to-mass conversion constants are given in Table 3.

Table 3: Ratio to Mass Conversion Constant.

Coefficient	Value/ Explanation	Source
υ_i	0.1538m³/kg binder material	Calculated from functional unit: ρ= 2400kg/m³ concrete, 13.33% binder in mix
V_i	0.4615m³/ kg coarse aggregate material	Calculated from functional unit: ρ= 2400kg/m³ concrete, 40% coarse aggregate in mix
δ	0.3077m³/ kg fine aggregate material	Calculated from functional unit: ρ= 2400kg/m³, concrete, 26.67% in mix
R_i	Volume ratio of *i* binder and j aggregates in mix design s.t ∑ R, ∑ R = 1	Input variable - determined by user of model

The transport of aggregate from quarry or other sources to batching plant adds to the environmental impact. Transportation accounts for 20% to 40% of the total carbon dioxide emissions by aggregate industry as a whole. European Commission figures estimate that the carbon emissions from different aggregate minerals transport options are approximately: 3.527 E-4 lb CO_2e/lb/mi (0.00016 kg CO_2e/kg/km) for road, 9.04 E-4 lb CO_2e/ lb/ mi (4.1E-4 kg CO_2 / kg/ km) for rail and 2.5 E-5 kg CO_2 / kg/ km (5.5 E -5 lb CO_2e/ lb / mi) for water (*Reducing the Environmental Effect of Transporting Aggregate; www.sustainableaggregate.com*). The average transport for aggregates by road delivery is 50 km (31.0686 mi), rail delivery is 150 km (93.2057 mi), and barge delivery 90 km (55.9234 mi). Therefore, the emission factor due to the transportation of aggregates to the batching plant and concrete to the site is considered in the model.

This approach has its disadvantage in terms of accuracy and validity risk. As previously mentioned, each constituent part of the model contributes to the overall impact independently; therefore the possibility of identifying interaction effects between the constituents is omitted. Additionally LCA case study data recorded from different locations and conditions generally does not include localized environmental impact in the model, such as landfill space and eutrophication potential, which is significant in concrete. Even for globally applicable errors such as CO_2e emission, representing impact as a linear function depends on multiple factors, which makes the model susceptible to truncation errors that in some cases can skew LCA results by as much as 50 percent (Lenzen, 2000)

Finally, as is the case with all LCA synthesis studies, there are a large number of nonrandom differences between LCA test designs that cannot be controlled within a comparative LCA framework, and thus must be included as error. While its disadvantages preclude its applicability in particularly complex systems or in applications where LCI accuracy validity are sensitive, the user-friendly model design lends itself to use in situations where life-cycle impact needs to be roughly estimated where LCA data are not widely available, or as a screening process for directing further LCA research or experimenting with concrete factors in environmentally-friendly concrete process and mixture design.

To demonstrate the use of the user-friendly model for the LCA, a set of tests were constructed to assess the CO_2e emission (kg) per functional unit, using the impact factor constants determined from LCA case studies as per Table 1. The weighted model for one highway mile (6458 tonnes) of concrete is as follows:

$$I_{CO_2e} = \frac{k_f\, C}{SL} \qquad \text{Eq. 4}$$

(note: k_f is a constant for the conversion to the function unit: k_f= 6.458E6 kg/highway mile) C was calculated for a number of different concrete mixture designs with varying percentages of FA and RCA shown in table 3 and 4. These percentages are based off of the baseline mixture ratio discussed previously, which uses a ratio of 1 part cementitious material, 2 parts dry fine aggregate, 3 parts dry coarse aggregate, and ½ part water. Therefore, the percentages in Tables 3 and 4 are percentages of these mixture ratios.

Table 4: Traditional mixture and Concrete with various ratios of RCA and various ratios of FA

Mix	Description	RPCement	RFAsh	RNCA	RNFA	RRCA
Control	Reference mix	1	-	1	1	-
RCA_{30}	RCA 30 % replacement	1	-	0.7	1	0.3
RCA_{40}	RCA 40 % replacement	1	-	0.6	1	0.4
RCA_{50}	RCA 50 % replacement	1	-	0.5	1	0.5
FA_{20}	FA 20% replacement	0.8	0.20	1	1	-
FA_{25}	FA 25% replacement	0.75	0.25	1	1	-
FA_{25}	FA 30% replacement	0.7	0.30	1	1	-
FA_{35}	FA 35% replacement	0.65	0.35	1	1	-

Consider: **RPCement –** Ratio of Portland Cement**, RFAsh-** Ratio of Fly Ash**, RNCA-** Ratio of Natural coarse aggregate, **RNFA –** Ratio of Natural Fine Aggregate**, RRCA-** Ratio of Recycled Concrete Aggregate.

To establish a baseline for comparison, the impact of a traditional Portland cement concrete mixture (Control) with no substitutions of cementitious material (RPortland = 1, RFA = 0) and 100 percent virgin aggregate was analyzed first. As previously stated, a historical study by various U.S. state transportation departments determined an average service life of concrete pavement is to be 39 years *(Van den Heede & De Belie, 2012)*. Thus, one highway mile of traditional pavement concrete has a CO_2e life-cycle impact of 21,589 kg CO_2e per highway mile per year. As mentioned before, in this case, impact from transportation was built into the CO_2e impact data, for the estimated 80.46 km (50 mile) radius. After the control mixture was analyzed, three mixtures were analyzed that replaced the coarse aggregate with RCA at 30%, 40%, and 50% replacement levels, while keeping all other constituents the same. The next cases analyzed replaced the Portland cement with FA at 20%, 25%, 30%, and 35% replacement levels.

Following the initial eight cases, additional models were analyzed to determine the impact of using both FA and RCA within the same mixture. These cases studied the traditional mixture, substituting the Portland cement with

35%, 30%, 25% and 20% with FA and 50% and 40% of coarse aggregate with RCA within the same mixture. Table 5 outlines the concrete mixtures with the replacement of Portland cement and coarse aggregate with FA and RCA respectively in the same mixture.

Table 5: Concrete mix with variable ratios of both RCA and FA mix.

Mix	Description	RPCement	RFAsh	RNCA	RNFA	RRCA
M20/40	FA 20% + RCA 40 % replacement	0.8	0.20	0.6	1	0.4
M20/50	FA 20% + RCA 50 % replacement	0.8	0.20	0.5	1	0.5
M25/40	FA 25% + RCA 40 % replacement	0.75	0.25	0.6	1	0.4
M25/50	FA 25% + RCA 50 % replacement	0.75	0.25	0.5	1	0.5
M30/40	FA 30% + RCA 40 % replacement	0.7	0.30	0.6	1	0.4
M30/50	FA 30% + RCA 50 % replacement	0.7	0.30	0.5	1	0.5
M35/40	FA 35% + RCA 40 % replacement	0.65	0.35	0.6	1	0.4
M35/50	FA 35% + RCA 50 % replacement	0.65	0.35	0.5	1	0.5

Consider: **RPCement –** Ratio of Portland Cement**, RFAsh-** Ratio of Fly Ash**, RNCA-** Ratio of Natural coarse aggregate, **RNFA –** Ratio of Natural Fine Aggregate**, RRCA-** Ratio of Recycled Concrete Aggregate.

4. Results

4.1. Life Cycle Impact Assessment

After the mixture ratios and GHG per-weight impact coefficients were determined, the values were analyzed using Eq. 4. Each mixture was analyzed individually and the results for the life cycle impact assessment are show in Figures 3 – 6. Figure 3 shows the results from mixture designs as specified in Table 4, which contains the traditional mixture (control) with three mixtures containing variable replacement RCA (30, 40, and 50%) replacement of coarse aggregate and four separate mixtures with variable FA replacement (20, 25, 30, and 35%).

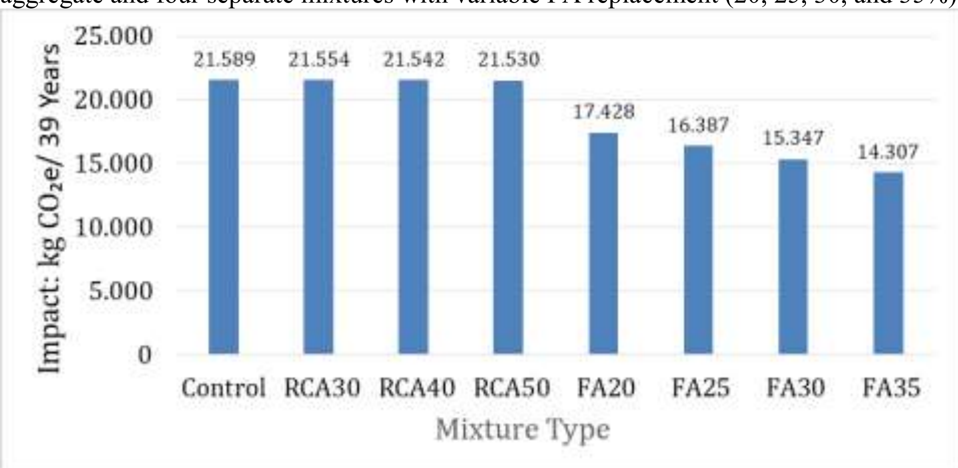

Figure 3: Impact of concrete with RCA and FA.

Figure 3 shows a negligible advantage of replacing coarse aggregate with RCA. This is expected for CO_2e impact, considering the amount of work involved in the demolition, crushing and cleaning of RCA *(Knoeri et al., 2013)*. The impact of demolition process is identical for all end-of-life scenarios and RCA substitution may prove to be more impact-efficient in other sources of environmental impact, such as natural resources preservation and waste disposal will be avoided. Recycling of concrete depends on the transportation distance to the concrete recycling plant and then to the batching plant, but one advantage of using RCA in paving is that recycling of concrete is traditionally completed on site. Therefore if RCA is recycled on site, the transportation value would be reduced to zero in Equation 2 and the overall impact would be reduced.

Figure 3 also demonstrates that an increase in percentage of FA reduces the GHG emission impact, by a minimum of 4,161 kg CO_2e. FA in concrete offers numerous structural and environmental advantages *(Dhir 2006)*, including the reduction of embodied GHG emissions. O'Brien K.R et al., (2009) reports that GHG emission factor for FA is very minimal and their study gave the critical distance for FA transportation (by articulated truck) to be 11,000 km (Emission Factor – 0.000209 kg CO_2e / km/ t) and still deliver a net saving in GHG emissions if used to replace Portland cement.

To determine the impact of concrete produced with both FA and RCA an additional analysis was done that included both. The previous analyses showed a marginal reduction in GHG emissions from the inclusion of RCA replacement of coarse aggregate, whereas replacing cement with FA showed a large reduction in environmental impact therefore there might be a break-even point due to the inclusion of both. Therefore an analysis was completed on mixtures that contained both coarse aggregate replacement with RCA and Portland cement with FA within the same mixture, as outlined in Table 5, and the results are shown in Figure 4.

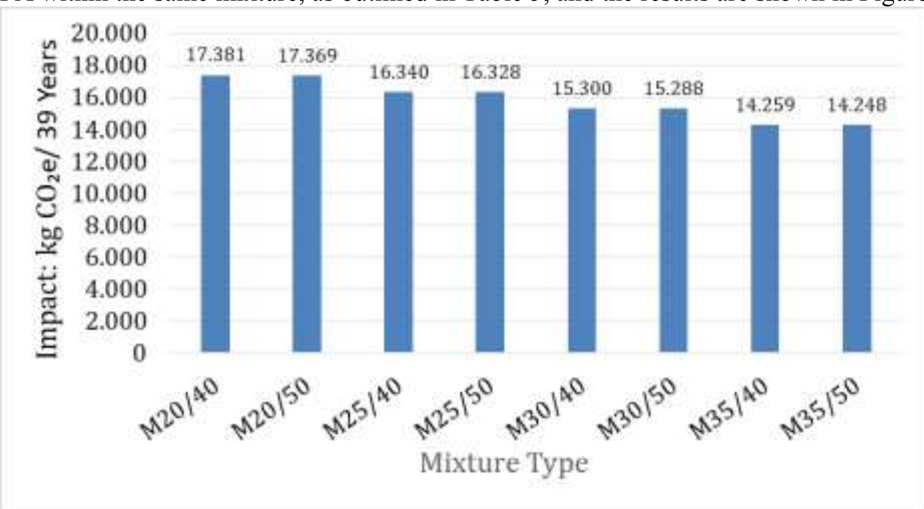

Figure 4: Impact of concrete with variable ratios of both FA and RCA.

The results from the combined RCA and FA trial ultimately demonstrate a reduction in GHG when including both RCA and FA. Figure 4 shows a general downward trend with an increase in both FA and RCA. The highest replacement mixtures, M35/40 and M35/50 with 35% replacement of FA and 40% and 50% replacement of RCA, respectively, have a distinct reduction in CO_2e emission compared to the control mixture (21,589). It is noticed that when the FA replacement is held constant and the percentage of RCA is variable, there is negligible difference between the two mixtures. For example, $M_{20/40}$ produced an impact value of 17,381 kg CO_ce and $M_{20/50}$ had an impact value of 17,369 CO_2e, which is a difference of only 12 kg CO_ce and a percent difference of only 0.023%. This exact difference is noticed between all mixtures in which the FA replacement value is held constant and the RCA value is changed. Therefore, a 10% increase in RCA replacement leads to reduction of only 12 kg CO_ce. This result demonstrates a point of minimal return for RCA replacement when FA replacement is also used in the same mixture. To further show this, an additional analysis was completed on the traditional mixture with 20% Portland cement replacement with FA and range of 0 – 100% coarse aggregate replacement in 10% increments, as shown in Figure 5.

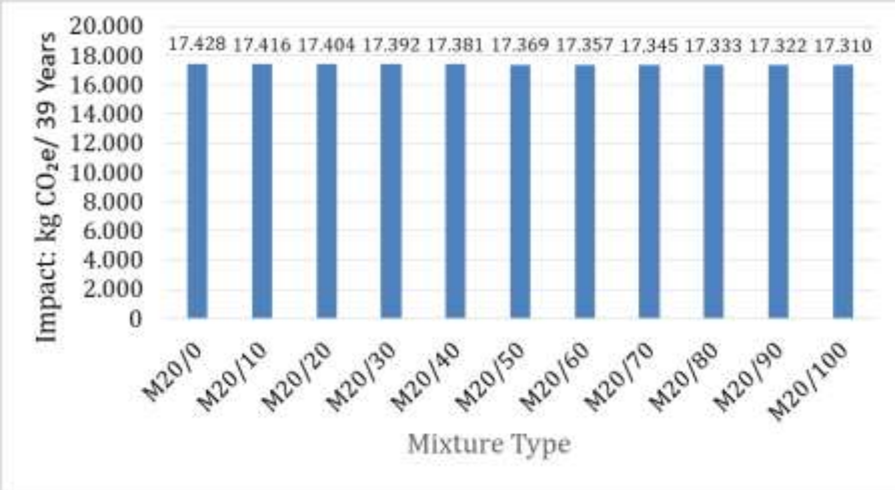

Figure 5: Impact of concrete mixture with 20% FA replacement and 0 – 100% RCA replacement.

Figure 4 shows the previously mentioned point of minimal return when including both FA and RCA in one mixture when the RCA percentage is changing from 0 – 100%. With the scale as it is shown in Figure 4, it is actually difficult to see any difference between the 0% RCA mixture and the 100% RCA mixture when the FA is held constant. It is observed that the higher impact of processing and using RCA eventually counter balances the reduced impact of using FA.

It can be seen that FA and possibly other SCMs provide the most benefit to the life cycle impact of concrete. As mentioned above, concrete with 20% to 35% replacement of Portland cement with FA gives a service life of 60 years *(Van den Heede & De Belie, 2012)*. The mixtures investigated in this study use a service life of 39 years for comparison as 39 years is the average service life of concrete pavement, however, Eq. 4 shows that as the SL increases, the impact will decrease, therefore mixtures with FA replacement will demonstrate an even higher impact than presented. Therefore, it can be concluded that concrete with SCMs can be beneficial if we consider the life cycle impact of concrete. To demonstrate the effect of a longer service life on the impact of the concrete mixtures investigated in this study, the same analysis was completed however the SL was increased to 100 years, shown in Figure 6.

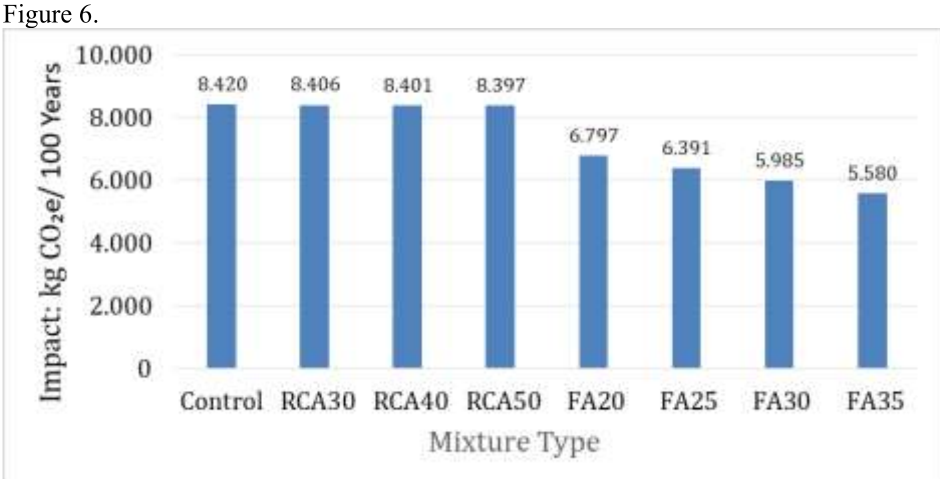

Figure 6: Impact of Concrete with RCA and FA at 100 year SL.

As seen in Figure 6, the model can produce results for longer service lives and for one of 100 years drastically increases the impact of all mixtures. Comparing just the control sample for 39 years (21,589 kg CO_2e) to 100 years (8,420 kg CO_2e) shows an 87.8 % difference in overall impact. Since each mixture is a proportion of each other an the only variable changed in this SL analysis, all values will be proportionally reduced by 87.8 % due to an increase in SL of 61 years. A visual representation of Equation 4 and the impact of SL can be seen in Figure 7.

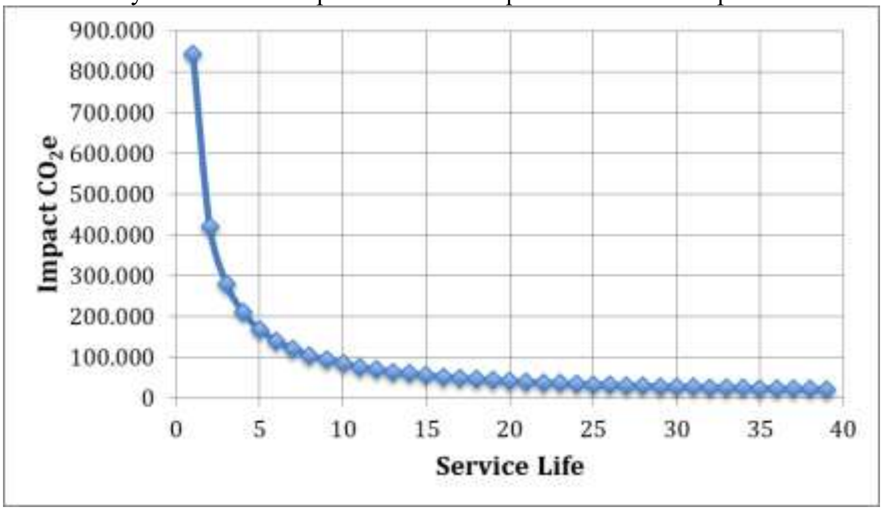

Figure 7: Traditional mixture (control) impact throughout a varied service life up to 39 years.

Figure 6 shows that the impact reduces with time i.e. increase in the service life decreases the impact of emissions. Such extended life span conserves resources by reducing maintenance and the need for reconstruction.

4.2. Valuation and Recommendation

FA has the potential to reduce GHG emissions globally by increasing the ratio of FA and other SCMs the estimated environmental impact is reduced. The growing usage of FA should resolve the issue of FA disposal and the GHG emissions due to concrete industry. Also, with greater quantities of FA, the durability of concrete related to resistance to sulfate attack and chloride-induced corrosion is further enhanced. Further, the use of FA in concrete supports sustainable construction. Strength and operational requirements of the concrete mix should also be considered while replacing the cement with FA. Environmental impact with the use of RCA only is slightly larger than for the coarse aggregate. The transportation distance of RCA is are smaller than the aggregate from the rivers, the ratio of RCA and natural coarse aggregate was assumed to be 15 km — 100 km, when recycling plant is located much closer to the concrete plant than the place of aggregate extraction (*Marinkovic et al; 2014*). The benefit is from recycling the concrete waste and reduction in depletion of the natural mineral resource. Additionally, an advantage of RCA in a concrete paving project is that the RCA can be recycled on site from the removal of the existing pavement, which reduces the overall impact from transportation.

5. Conclusions

Many studies have demonstrated the ways in which producers of the cement and other concrete components can benefit from LCA-based improvements, but the benefits of the LCA approach can be expanded further downstream by modeling LCI as a function of concrete inputs that are readily available to end users. This study developed a user-friendly linear LCI of concrete as a function of replacement level of alternative binder and aggregate materials to allow for impact comparison of different concrete mix designs, and demonstrated how this could be accomplished using data from current case studies in concrete LCA. The use of FA and RCA in concrete allows various environmental advantages including the reduction of GHG emissions by replacing the Portland cement and natural aggregates. Use of RCA in the concrete mixture can help in reducing the disposal of construction waste and depletion of the natural aggregates. The user-friendly linear model discussed in this paper is an example of a potentially useful tool for a rough LCA impact estimation when comparing the estimated impacts of different ratios of FA and RCA. Concrete service life was revealed as a particularly critical factor in determining the overall LCI of concrete. However, FA was revealed to be the most impactful SCM investigated with a minimum decrease of 4,161 kg CO_2e per kilometer of pavement from the control mixture. Incorporating RCA into the concrete mixture only resulted in a 12 kg CO_2e reduction due to the additional energy required to process the material. This model demonstrates the impact of just a few alternative concrete constituents, however, a contractor or concrete producer can use the developed model to assess the impact of other SCM binder materials such GGBFS or Silica Fume. This simple input-output model is simple to use and only requires the use to identify the emission value of their specific constituents and plug each value into the developed equations. A spreadsheet can be easily developed with slight modifications in the mixture ratios, such that an optimum mixture can be identified. This type of user-friendly model, which can be used throughout the industry, will allow effective and understandable impact studies to be produced, which will aide in an enhanced sustainable design and construction.

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