Auditing carbon reduction potential of green concrete using life cycle assessment methodology

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Abstract. The production of concrete in its traditional form have reported a notable impact on the environment in terms of resource depletion and the carbon footprint it generates in the entire life cycle. To reduce these impacts, the ‘Green Concrete’ concept is at focal point of research in the construction industry. The advantage of resource conservation of ‘Green concrete’s is evident from usage of industrial by-products like fly ash, blast furnace slag, silica fume etc. as alternative binder materials and recycled wastes like construction and demolished waste and other industrial wastes as aggregate fillers. However, the quantification of environmental impact of such concretes in terms of most crucial emissions, like CO₂ emissions in an objective way would confirm the eco-friendly face of ‘Green concrete’. Life cycle assessment (LCA) is one of the most trusted tools to arrive at carbon score of such green concrete. This paper presents a step-by-step procedure of estimation of carbon footprint of a green concrete considering all possible phases of the life cycle of concrete including the post use phase. The conclusive findings from available literature for different types of ‘Green concrete’ are also presented to reflect the environmental advantage/disadvantage. The effect of system boundary, carbon uptake and allocation of impact are also discussed with reference to the results available in the literature.

1. Introduction
Over decades, concrete has been considered as a boon to the construction industry. However, the negative and irreversible impacts of its production, occurring collaterally, have categorized it as an eco-foe material in the most traditional form [1]. The production of concrete has several environmental impacts (EI). The two major EIs of concrete production are emission of greenhouse gases (GHGs) in the atmosphere and depletion of natural resources [2-5]. The emission of anthropogenic carbon dioxide (CO₂) and other heat trapping gases are reported to be highly significant in life cycle of concrete when compared to similar optimized structures of steel and wood. Each activity in concrete linked chain contributes to carbon emission process. Energy demanding activities right from extraction and processing of raw materials, transportation phase, concrete making phase, service life phase, demolition activity after service life and reuse or disposal phase cannot exist without any emissions [6-8].

Carbon footprint is an important tool to evaluate the EI generated by concrete production and its components. Originally, it was expressed as an area for assimilation of CO₂ emissions generated during the life cycle of a manufactured product. The problem of global warming on international agenda has modified the concept of carbon footprint. The CO₂ emissions along with other gases like methane (CH₄) and nitrous oxide (N₂O) has been identified as one of the most prominent reasons for climate change in middle of 20th century in terms of global warming. These emissions are also referred as GHGs. So, carbon footprint is no longer represented as an area, but the amount of GHGs associated with a product throughout its life cycle. All the emissions responsible for this global warming phenomenon are
categorized under one term called as ‘Global warming potential’ (GWP) in terms of kg CO$_2$-equivalent [9].

The global annual production of concrete is estimated as 25 billion tons or 3.8 tons per capita per year [10, 11]. The CO$_2$ emissions for a normal strength concrete mix with Ordinary Portland Cement (OPC) ranges between 240 and 320 kg CO$_2$-equivalent per cubic meter of concrete [7,12]. Unit wise EI of concrete is relatively small compared to other building materials but its high global production has resulted in a significant impact [13, 14]. Concrete accounts for 70% of CO$_2$ emissions among the major building materials [15].

1.1 Green concrete technology

The development of ‘Green Concrete’ is a welcome initiative to minimize the EIs associated with GHG emissions. Various supplementary cementitious materials (SCMs) that are byproducts from another industrial process such as fly ash (FA) or granulated blast furnace slag (GBFS) are used as an alternative for partial replacement of pure cement to contribute towards reduction in carbon emissions [16,17]. The substitution of natural aggregates (NA) with recycled aggregates (RA) or other suitable industrial wastes presents the second phase ‘green concrete’ technology reducing the EI through preservation of natural resources and minimization of waste disposal [18].

The adoption of ‘Green Concrete’ technology is thus rectification of mix design parameters of ordinary concrete to obtain a concrete with reduced environmental impacts without sacrificing its workability, mechanical strength and durability. The ‘greenness’ of such concretes is questionable unless its environmental assessment is carried out throughout its life cycle and compared with ordinary concrete [19]. As a debatable scenario, use of FA or GBFS as a substitute to OPC is claimed to reduce GHG emissions substantially, but the emissions resulting from transportation of this substitutes may outscore the basic reduction benefit at material level. Such acclaimed benefit is not quantified most of the times [20]. In another scenario use of RAs to replace NAs indicates environmental benefit with respect to resource consumption. However, such recycled aggregate concrete (RAC) demands additional cement to attain a comparable strength, thereby increasing carbon emissions in this so called ‘Green Concrete’ [21-22]. This clearly signifies that each type of concrete is unique with regards to its EI assessment. Therefore, a holistic approach is recommended for analysis and quantification of overall impact of production of these green concretes. Life cycle assessment (LCA) method is considered as most suitable method to obtain comparable results for environmental impacts for different types of concretes [23]. This method is found to be advantageous for assessing environmental implications of green concrete in comparison with traditional concrete.

1.2 Life cycle assessment- a standard tool

LCA is an analytical method which helps in systematic identification, evaluation and minimization of EI of a particular process [24]. It can quantify the emissions, consumption of resources and energy for all processes involved in transformation of raw materials into final products. It can also extend the analysis to useful life period of products, final disposal of products and byproducts and recycling process if any [25]. As per ISO 14040, LCA is defined as “compilation and evaluation of the inputs, outputs and the potential EIs of a product system throughout its life cycle” [26]. It is a systematic analytical method that enables identification and evaluation of EI of a specific process along with material and energy flows.

LCA is considered as an advantageous and standard tool for environmental evaluation of construction material like concrete [27, 28]. It is because, the concrete life cycle can be subdivided into small unit processes from raw material extraction to its disposal [29, 30]. This evaluation extends from the start of the primary life to the end of secondary life of concrete. The primary life begins from the time of extraction of raw materials for concrete production to the completion of demolition of the structure. The secondary life commences when demolished concrete is recycled and is utilized in new construction, and it culminates when the built component reaches the end of its service life [6]. LCA can be used for methodical analysis and quantification of EIs of both traditional and green concretes with a known fact
that the concrete laid for a structure remains locked during its long service life [23]. It can give objectively quantified environmental score for low cement concretes or green concretes [20]. LCA analysis can be used for entire life cycle or part thereof by specifying the system boundaries of analysis. After developing data collection methodology for considered life cycles, assessment of potential environmental and human health impacts is carried out [31].

1.3 Carbon assessment of green concrete using LCA - a review

The use of byproduct materials from industrial sector as replacement of OPC in concrete has received increasing attention over last few decades [32, 33]. The most popular inventory of such materials includes FA, GBFS, Silica Fume (SF), Metakaolin (MK) etc. The research and innovations in this sector have added new byproducts such as Rice Husk Ash (RHA), Lime stone flour (LSF) etc. to this inventory. Extensive research on their functional suitability as substitute materials for cement is available across the globe. The assessment and quantitative analysis of the changes in EI caused by substitution of such materials in concrete is also gaining importance in research studies nowadays.

Nisbet & Van Geem [34] presented LCA of Ready mixed concrete (RMC), precast concrete and masonry concrete block with 15 to 20% replacement of FA in concrete having compressive strength between 20 to 35 MPa. The results clearly indicated that cement content of the mix is the decisive parameter of CO$_2$ emissions in all the cases.

Prusinski et al. [35], in a quantitative assessment reported that GBFS leads to a reduction of CO$_2$ emissions of 29-46% for RMC as well as precast concrete. Around 50% lower carbon emissions were reported for precast concrete mixtures with GBFS and SF along with appreciable improvement in functional performance. A similar effect of GBFS was also noted in case of Ultra high strength performance concrete (UHPC) in a study by Kim H. et al. [36].

The study of FA blended concrete by O’Brien et al. [37] estimated GHG emissions as a function of FA content in the mix. The limiting transportation distance of FA for a breakeven scenario of equivalent emission by replaced cement was determined for three transportation modes. It was concluded that FA will reduce the embodied GHG emissions as long as it can reduce cement content without sacrificing the functional property requirements of concrete.

Life cycle CO$_2$ assessment of 560 concrete mix designs in Korea was undertaken by Park et al. [38] by categorizing the mixes as per SCM type, strength class and season of the year. It was reported that CO$_2$ emission increases with increase in strength class showing linear correlation. Using a regression analysis, a regression equation with high coefficient of determination depicting strength class and CO$_2$ emission relationship was obtained. For a concrete manufactured in standard season use of SCMs lowered the emissions by as much as 47%, whereas for concretes produced in winter an increase of emissions by 5% was reported due to addition of more cement to meet curing requirements.

Celik et al. [39] performed environmental assessment of concrete with binary and ternary mixes of OPC, HVFA and LSF. The study inferred that 93% of total GWP of concrete production sourced from OPC can be reduced to 69% by introduction of SCMs in concrete.

Jiménez et al. [40] carried out environmental assessment of RAC mixes designed using equivalent volume method and other general methods of mix design and used FA and GBFS blended cements for sensitivity analysis. It was reported that use blended cements lowers CO$_2$ emissions by about 17-27%. In Indian subcontinent, Gettu et al. [41] showed that concrete with FA, GBFS and limestone calcined clay cement (LC3) reduces GWP emission from 6% to 26%.

Tait & Cheung [42] compared the EIs of OPC concrete with blended cement concretes with strength and durability as functional benchmarks. The studies confirmed the improvement of environmental sustainability by use of blended cements, with strong recommendation for GBFS blends for optimum mix designs.

Flower & Sanjayan [7] provided the most popular and systematic LCI of concrete raw materials along with production process and transportation activities. Two design mixes of 25 MPa and 32 MPa strengths replacing OPC with 20% FA and 40% GBFS were compared for CO$_2$ emissions with that of traditional concrete. Reduction of CO$_2$ emission by 13-15% and 22% for GBFS was a key finding in the
analysis. Superiority of GBFS in reduction of EI by virtue of its substitution potential as stated by García-Segura et al. [43] and Van den Heede & De Belie [20] was confirmed by the authors.

Kurda et al. [5] carried out an analytical study to explore the effect of simultaneous variation of FA and RA in concrete and confirmed that FA exhibits significant decrease of 32-60% for all impact categories. GWP showed a linear decline with increase in FA substitution levels.

The aggregates represent about 70% volume of the concrete. They are responsible for about 15% of the total CO₂ emissions from concrete. These emissions are mainly due to energy requirements in their extraction and processing [44]. The replacement of aggregates in concrete by recycled waste from construction and industrial sector is done to tackle the long-worrying problem of resource depletion and waste disposal. This is the second phase of ‘green concrete’. Extensive studies across the world have answered the questions raised by these replacements on the functionality and durability of such concrete. However, the investigations are yet to confidently answer the question whether substitution of aggregates can reduce the EIs such as carbon emissions.

McIntyre et al. [45] conducted evaluation of GHG emissions for RAC for North American recycling operations. The analysis concluded that 20% replacement of virgin coarse aggregates by RA is a threshold substitution value without sacrificing functional requirements of concrete. Beyond this threshold value RAC demands additional cement to satisfy the strength criteria which is responsible for proportionate increase in the environmental load of RAC.

Liu et al. [46], in their EI assessment study of RAC verses NAC stated that GHG emission for production of RA is 57% lower than NA production however, 64% additional cement is required by RAC to attain the mechanical strength at par with equivalent grade NAC which hikes the emissions. Marinković et al. [22], in their specific case study reported that EI of RAC having 100% coarse RA is slightly larger than that of NAC. Jiménez et al. [9], Kleijer et al. [13] and Serres et al. [47] also showed that GWP of RAC is slightly lower than that of ordinary concrete due to low emission factor embodied with RA subject to minimum transportation distances of NA and RA.

Faleschini et al. [48] and Anastasiou et al. [49] evaluated life cycle of concrete containing partial substitution of EAF slag as aggregates and compared it with conventional concrete. Comparatively, higher impacts were noted for EAF slag concrete due to higher cement demand. However EI evaluation concrete with EAF slag, foundry sand and RA by Turk et al. [50] reported an environmental benefit of 15-35% for foundry sand and EAF slag incorporation individually and 12-26% when RA was used individually or combined with foundry sand and FA. Specific gain in GWP was however within 5% only. Similar synergistic effect of using GBFS and limestone as cement substitutes along with rapid cooling EAF slag as aggregate substitute was also noted by Kim H. et al. [36] confirming 37% reduction in GWP value.

Braga et al. [2] analyzed 216 concrete mixes from 24 reference studies to evaluate their EI taking into account cement content, admixture dosage and w/c ratio. For a given strength class, increase in RA substitution and w/c ratio reported declining trend in GWP, whereas no conclusive trend was evident for variation in admixture dosage.

A case study of RAC from Paris region was taken up by Fraj & Idir [21]. The study evaluated the effect of grades of RA and their delivery distances on EI of RMC. It was proved that higher grade of RA reduces GWP of concrete due to lowered cement consumption.

1.4 Objective of study
In majority of the LCA studies, the impacts are determined for the part of the life cycle. Life cycle from raw material extraction to concrete manufacturing that is, cradle to gate, is used as the most favorite scope of study. Few studies extended this analysis to include impacts during service life and/or demolition of concrete to account for complete primary life of concrete. However, the secondary life of concrete which includes reuse and recycling of concrete is yet to find an entry into LCA system boundary on a mentionable scale. The step treatment to this secondary life of concrete in LCA may be a source of error in estimation of EI, especially carbon emissions. Carbon uptake by concrete during and after use phase is a potential source of carbon reduction. Secondly, reuse of demolished concrete may
provide carbon saving through the activities that are avoided. These activities include transportation/levelling activities at the landfills and procurement activity of virgin aggregates. There is a need to detail out a step-by-step procedure of estimation of carbon emission considering all the phases of its life cycle. Few authors have presented such procedure only for cradle to gate system boundary [8, 37, 38, 51]. For the first time, this paper presents a systematic detailed procedure of estimation of carbon emissions of concrete in all the stages of its life cycle. This procedure is presented in the background of LCA methodology as per ISO 14040 standards. This study also focusses on other influential parameters affecting carbon assessment of green concrete. These parameters include functional unit of assessment, inclusion/omission of life cycle processes and allocation of impacts from upstream life cycle of waste products used in green concretes. The results of various studies in the literature are presented to underline the importance of each of these factors on life cycle carbon assessments of green concretes.

2. Methodology of LCA

The methodology of LCA is defined by ISO 14040 standards in four different well-defined phases. They are 1) Goal and scope definition – which defines objective and the context of study, 2) Inventory – which identifies the raw materials which are inputs of process, 3) Impact assessment- which identifies the impact of the process and 4) Interpretation- which evaluates the results and establishes the relationship between process flows and EIs [26, 52]. All the phases of LCA methodology are interlinked and interdependent as shown in figure 1.

2.1 Goal and scope definition

This step aims at clear definition of goal of LCA and its intended application. The key task at this stage is defining the Functional Unit (FU) and establishment of system boundary [53].

The FU is the basis on which LCA is carried out and it allows comparison of two products on functional equivalency. It plays a major role in assessment of EI. It provides the basis for quantification of all input and output data [54]. As per ISO 14040, it is defined as quantification of identified functions of the product [26]. For concretes, the basic FU is volume (1 m$^3$) or mass (kg). However, LCA results obtained only on basis of volume shall not hold good if it does not incorporate functional characteristics of concrete such as strength and durability [31]. E.g., EI of concretes of two different strength classes is bound to have variations due to the difference in their binder contents. So, a complex FU is desirable in comparison of impacts of diverse concretes. Selection of different FUs delivers different outcomes for the same product [55].

Establishment of system boundary is a key task in LCA. It determines which life cycle process/es of the product are to be included or excluded from the analysis. Decision of whether or not to include any process in life cycle of the product system is decided on objective and scope of study. E.g., if comparative study of EIs of two types of concretes is carried out and if any of the life cycle process is with identical quantitative parameters, the process is generally excluded from the system boundary [27]. As per European standards, life cycle stages of concrete are classified into three main phases.
1) Cradle to gate phase – This phase includes product stage of manufacturing of concrete from extraction and processing of basic raw materials as well as secondary material inputs, their transportation and manufacturing of concrete.

2) Gate to grave phase - This phase includes construction process stage, use stage and end of life stage of concrete. The construction process stage includes transportation of concrete and installation to the building site. The use stage includes application, maintenance, repairs, replacement and refurbishment of concrete during its service life. The end-of-life phase includes deconstruction or demolition of concrete, transportation of demolished concrete, waste processing for reuse, recovery and/or recycling and disposal of part or full waste.

3) Grave to cradle phase - This phase includes reuse, recovery and/or recycling potential of concrete.

These three phases define the three most general LCA system boundaries i.e., ‘cradle to gate’, ‘cradle to grave’ and ‘cradle to cradle’ as presented in figure 2. The system boundary considered for the LCA is usually indicated on a flow diagram of life cycle process of the concrete and is represented by enclosing the processes included in the analysis within a closed area. The other processes outside the enclosed area forms the part of life cycle of the concrete but are not included in LCA in the domain of Goal and scope of analysis.

![Figure 2: Flow diagram showing life cycle phases of concrete & system boundaries.](image)

2.2 Life cycle inventory (LCI)
The key task in this stage is the development of methodology of data collection. Establishment of data quality, identification of sources of data, managing missing data and compilation of data for the activity or the process which is analyzed is the primary objective of this step. It also involves the calculation procedure to quantify the inputs and outputs of a product. This is best analyzed by preparing a process flow diagram incorporating different processes as shown in figure 2. It aims at describing product specific and impact specific parameters which might be the demand of holistic LCA. A comprehensive, broad and a credible LCI, thus determines credibility of LCA [23].

In green concrete technology, the industrial products like FA and GBFS and other SCMs are included in the life cycle of concrete as waste products, without carrying any burden of EIs of the multifunctional process from which they are produced. However, their extensive use in recent decades has attached a quantitative and economic value to these products. Thus, allocation of the impact of upstream process of production of such products is an integral part of inventory and impact analysis (see section 2.2.1). Secondly, concrete has a profound ability to chemically react and consume the air borne CO\(_2\) by a process called carbonation during its service life and after the end of service life. This uptake of CO\(_2\) also is an integral part of LCA which is seldom accounted (See section 2.2.2).

In case of recycled concrete after post demolition phase, the avoided impacts due to avoided extraction of equivalent volume of NA and avoided landfilling should be accounted while accounting for net impact [56].
These three considerations are the sources of deviation of the results from actual values of net CO\textsubscript{2} emissions [6, 7, 43].

2.2.1 Influence of allocation procedure on LCA of concrete. The byproducts from industry which are used as SCMs in concrete are a result of a multifunctional process. E.g., the combustion of coal produces both electricity and FA. So, the EI caused by coal burning should be attributed to both electricity and FA as their embodied impacts when used in their downstream chain link. The process of distribution of these EIs in a multifunctional process to resulting main products and byproducts is called allocation [57, 58]. The GWP allocated to a byproduct is the fraction of total GWP associated with the primary process from which it is generated. This fraction is called allocation coefficient. This allocation coefficient depends upon the mode of allocation. There are three modes of allocation.

1) No allocation method- when the byproduct is totally considered as waste without any allotment of GWP form primary process and thus, zero value of allocation coefficient.

2) Mass allocation method- In this method GWP is allocated to the main product and byproduct in the ratio of their masses, i.e., mass allocation coefficient is the ratio of mass of byproduct to the total mass of main product and byproduct.

3) Economic allocation method – In this method GWP is allocated to the main product and byproducts proportional to their economic values or revenues i.e. economic allocation coefficient is the ratio of economic value of the byproduct to the total economic value of main product and byproduct [14, 57]. The effects of allocation approaches for mineral additives on LCA of cement-based materials have been exhibited in various studies [57, 58].

2.2.2 Influence of carbonation on LCA of concrete. The air borne CO\textsubscript{2} diffuses into the pores of concrete and chemically reacts with calcium oxides present in hardened cement products to form calcium carbonate. This chemical process is called carbonation of concrete [59].

\[
\text{Ca(OH)}_2 + \text{CO}_2 \rightarrow \text{CaCO}_3 + \text{H}_2\text{O}
\]

Thus, carbonation is a chemically reverse process to calcination of cement-based materials. The carbonation is very negligible during the primary life of concrete in comparison to the significant emissions resulting from manufacture phase of concrete [60]. The carbonation is considerably greater when more concrete surface is exposed for carbon absorption post demolition and recycling phase [6, 59, 61]. Approximately 6.5% of total CO\textsubscript{2} emission from cement production is reabsorbed during service life of concrete and 2 to 15% of CO\textsubscript{2} is reabsorbed during recycling phase of concrete [62].

2.3 Life cycle impact assessment (LCIA)

This step aims at evaluation of potential impacts resulting from various inputs and outputs for various steps considered in the life cycle inventory of a product. As per ISO 14044 [26], LCIA involves two mandatory steps, namely selection and classification of impact categories and characterization. The selection and classification of the impact category aims at defining the EIs by their impact pathway and impact indicator. The characterization aims at quantitative modeling of each impact in terms of impact score with a common unit to all contributions for that particular impact category [63]. Various impact categories are listed in European standard EN 15804 [64]. Global warming potential (GWP) is the impact category housing the impact of carbon emission. Thus, GWP is considered synonymous with life cycle CO\textsubscript{2} emission in LCA.

2.3.1 GWP impact assessment calculations. The most generalized relation for total GWP of concrete throughout the life cycle of a concrete mix per m\textsuperscript{3} considering all phases of its life cycle can be given by equation (1):
The GWP for all the raw materials in concrete manufacturing can be estimated using equation (2).

\[
GWP_{\text{raw materials}} = \sum (Q_i \times E_{RM})
\]

\(i = 1, 2, 3...N\) for all the raw materials (2)

\(Q\) is the quantity of each material (tons) per m\(^3\) of concrete and \(E_{RM}\) is the CO\(_2\) emission factor per unit quantity of raw material (kg-CO\(_2\)/ton).

As per Society of Environmental Toxicology and Chemistry (SETAC) guidelines, inputs to a process need not be considered in LCA framework if 1) Input accounts for less than 1% of total mass of processed material or product, 2) They do not consume significant energy and 3) They do not contribute to toxic emissions [65]. With reference to these guidelines, the process inputs like admixtures are sometimes excluded from analysis [48]. The allocated impacts for the byproducts used as raw materials in concrete manufacturing process, as discussed at section 2.2.1 is considered at this stage of analysis.

The total emission resulting from transportation for various activities in concrete cycle can be obtained using equation (3).

\[
GWP_{\text{transport}} = GWP_{\text{RM-TR}} + GWP_{\text{CT-TR}} + GWP_{\text{DC-TR}} + GWP_{\text{RC-TR}}
\]

\(GWP_{\text{RM-TR}}, GWP_{\text{CT-TR}}, GWP_{\text{DC-TR}}\) and \(GWP_{\text{RC-TR}}\) are the GWP values for transportation of raw material to batching plant, manufactured concrete to placement site, demolished concrete to disposal or recycling plant and RAC to batching plant respectively.

The contributions from transport of raw materials and demolished concrete can be estimated using equation (4).

\[
GWP_{\text{RM-TR/DC-TR/RC-TR}} = \sum (Q_j \times D_j \times E_{TR})
\]

\(j = 1, 2, 3...N\) for the raw materials, demolished concrete, disposable concrete, RAC etc. (4)

\(Q\) is the quantity of each material (tons) per m\(^3\) of concrete, \(D\) is the distance transported (km) and \(E_{TR}\) is the CO\(_2\) emission factor per unit quantity of raw material per unit distance (kg-CO\(_2\)/t.km) which depends upon the transportation equipment used for corresponding materials.

The emissions from transportation of manufactured concrete to placement site is mostly estimated relative to density of concrete as indicated in equation (5).

\[
GWP_{\text{CT-TR}} = \delta_{CT} \times D_{CT} \times E_{TR}
\]

\(\delta_{CT}\) is the density of concrete (t/m\(^3\)), \(D_{CT}\) is the transportation distance to the placement site and \(E_{TR}\) is the CO\(_2\) emission factor for (kg-CO\(_2\)/t.km) for the used transportation equipment.

The manufacturing phase, use phase, demolition phase, disposal and/or recycling phases are energy consumption phases. The GWP for all these phases is directly proportional to the quantified amount of energy source (fuel and/or power) consumed in carrying out the process per m\(^3\) of concrete. The GWP for these phases can be calculated using equation (6):

\[
GWP_{\text{production/maintenance/demolition}} = \sum [P_k \times (E_p)_k]
\]

\(k = 1, 2, 3...N\) for the energy sources used for the process like electricity, fuel, etc. (6)

Where \(P\) is the quantified consumption of energy from used source per m\(^3\) of concrete (E.g., KWh of electricity or litres of oil per m\(^3\)) and \(E_p\) is CO\(_2\) emission factor per unit energy consumption (kg-CO\(_2\)/KWh of electricity or kg-CO\(_2\)/litre of Oil).
Any material consumption during use phase for maintenance, repairs or refurbishment should be analyzed for its CO$_2$ emissions and accounted per m$^3$ of repaired concrete. GWP against CO$_2$ absorption, that is, carbon uptake due to carbonation process during the use phase and after demolition of concrete can be calculated by using relationship at equation (7):

$$GWP_{carbonation} = x \times r \times C \times CaO \times M$$

(7)

Where $x$ is the calculated depth of carbonation (meters), $r$ is the proportion of $CaO$ within fully carbonated OPC that converts to $CaCO_3$ (assumed to be 0.75), $C$ is the amount of OPC in concrete per m$^3$, $CaO$ = Percentage amount of CaO in OPC by weight and $M$ is the is the dimensionless chemical molar fraction, CO$_2$/CaO taken as 0.79 [6, 61].

Finally, GWP due to the avoided impacts due to recycling if any, should be determined depending upon energy consumption for processing and transportation of the recycled components of concrete.

2.3.2 Databases and Software. From the discussions in the preceding section, it is clear that the estimation of GWP of concrete requires quantification of material inputs and energy inputs in a particular process in the concrete life cycle. These material and energy inputs are multiplied by respective CO$_2$ emission factors to obtain the components of total CO$_2$ emission for the complete life cycle. So, the reliable value of emission factors for the material or energy inputs is a key factor in LCA of concrete. Determination of the emission factors for each input is a complex and laborious process [28]. Availability of databases of such emission factors for GWP assessment has facilitated the LCA process to a great extent. These databases are developed to incorporate inventory data on a variety of products considering all the life cycle phases for that product. To make this study more efficient and less time-consuming, software tools are commercially available [66, 67]. Using this software packages, it is possible to generate results of LCA in tabular formats along with graphical presentations.

Table 1 gives the details about most common databases and software tools used for LCA of concrete. Ecoinvent database offers all necessary inventory data for concrete production, so it is an internationally accepted database [56].

| Database     | Software tool | Web Access                  | Country     |
|--------------|---------------|-----------------------------|-------------|
| Bath data    | x             | People.bath.ac.uk/cj219     | UK          |
| Boustead     | Boustead      | www.boustead-consulting.co.uk | UK         |
| Ecoinvent    | x             | www.pre.nl/ecoinvent        | Switzerland |
|               | Ecoit         | www.pre.nl                 | Netherlands |
| ELCD         | x             | http://lca.jrc.ec.europa.eu  | EU          |
| GaBi         | GaBi          | www.gabi-software.com       | Germany     |
| GEMIS        | GEMIS         | http://www.oeko.de/service/gemis/en/ | Germany |
| JEMAI        | JEMAI         | www.jemai.or.jp/english/index.cfm | Japan      |
| SimaPro      | SimaPro       | www.pre.nl                 | Netherlands |
| Spin         | x             | http://195.215.251.229/Dotmetnuke/ | Sweden     |
| TEAM         | TEAM          | www.ecobilan.com           | France      |
| Umberto      | Umberto       | www.umberto.de             | Germany     |
| USLCI data   | x             | www.nrel.gov/clc          | USA         |

2.4 Interpretation of results

This is the final step of LCA of any product. The key objective is to evaluate the results obtained from the analysis with respect to completeness, consistency and sensitivity [31, 69, 70].

2.5 Typical Green concrete composition and its GWP analysis using LCA
It is clear from the discussions in the previous sections that the quantification of EI is a necessity to rate a modified concrete on a green scale in comparison with the normal concrete mix. In this section, typical design mixes in which cement is replaced with FA and/or NA is replaced with RCA are selected from a study conducted by Kurda et al [5]. The GWP of these mixes is calculated and compared with GWP of normal concrete.

Eight concrete mixes with 0, 30 and 60% FA and/or 0 and 100% substitution of RCA for both coarse and fine fractions of NA are selected from the study. Table 2 shows the details of the selected mixes for a functional unit of 1 m$^3$ volume. Mix M$_1$ indicates control mix. Mixes M$_2$ and M$_3$ are the mixes with 30 and 60% replacement by FA. Mixes M$_4$ to M$_8$ are the mixes with 100% fine RCA and/or coarse aggregates replaced for natural sand and gravel in the control mix.

Table 2. Mix proportions for analysis of 1 m$^3$ concrete {Source: Kurda et al. [5]}

| Mix Designation | Characteristics | Cement (kg) | FA (kg) | Sand (kg) | Gravel (kg) | Fine RCA (kg) | Coarse RCA (kg) | Water (kg) |
|-----------------|-----------------|-------------|---------|-----------|-------------|---------------|----------------|-----------|
| M$_1$           | C100FA0F0C0     | 350         | 0       | 763       | 1060        | 0             | 0              | 186       |
| M$_2$           | C70FA30F0C0     | 245         | 105     | 747       | 1066        | 0             | 0              | 179       |
| M$_3$           | C40FA60F0C0     | 140         | 210     | 728       | 1074        | 0             | 0              | 172       |
| M$_4$           | C100FA0F100C0   | 350         | 0       | 0         | 1034        | 634           | 0              | 223       |
| M$_5$           | C100FA0F0C100   | 350         | 0       | 759       | 0           | 919           | 196            |           |
| M$_6$           | C100FA0F100C100 | 350         | 0       | 0         | 0           | 629           | 898            | 233       |
| M$_7$           | C70FA30F100C100 | 245         | 105     | 0         | 0           | 611           | 898            | 226       |
| M$_8$           | C40FA60F100C100 | 140         | 210     | 0         | 0           | 595           | 906            | 229       |

Cradle to gate system boundary was used for the analysis. GWP for production of 1 kg of each raw material in the mix as obtained by Kurda et al. [5] are listed in table 3. These are the emission factors which can be used for estimation of materials and process emissions for given FU of the mix. The transportation distances of various constituent materials were considered for a site-specific data in Portugal from a previous study by Braga et al. [2]. The transportation distance of cement and FA from market to concrete plant was 12.5 km, whereas, fine NA and coarse NA was procured from distance of 100 km and 37.5 km respectively.

Table 3. GWP (kg CO$_2$ eq) values for raw materials, transportation and concrete manufacture

| Concrete Constituents (kg) | Transportation (1kg/km) | Process(m$^3$) |
|---------------------------|-------------------------|----------------|
| Cement                    | FA                      | Fine Sand      | Coarse Gravel | Fine RCA | Coarse RCA | Water    | Articulated lorry/27t | Lorry /17.3t | Concrete manufacture |
| 0.898                     | 0.00392                 | 0.0014        | 0.0282        | 0.00465  | 0.00465    | 0.000133 | 0.0498            | 0.0657        | 4.65               |

Using the emission factors at table 3, the GWP values for all the mixes listed in table 2 are calculated for FU of 1 m$^3$ of concrete. The values of GWP for all the mixes are presented in table 4. The values of compressive strength of concrete at 28 days and 180 days of curing are also given in the table to explain the importance of consideration of a strength factor in FU along with volume of concrete.

Figure 3 shows the plot of GWP values for various mixes analyzed for 1 m$^3$ of concrete. It can be seen that the mixes M$_2$ and M$_3$ with FA blending shows a saving of 25.9% and 51.9% GWP respectively, compared to the normal concrete. This benefit further extends to 33.7% and 59.8% for mixes with FA and RAC in case of mix M$_7$ and M$_8$ respectively. It should be noted that there is no significant reduction in GWP for concretes in which only RCA was substituted for NA with maximum benefit of 7.75% saving in GWP. These benefits are for volumetric FU of 1 m$^3$. 
Table 4. GWP and compressive strength values of concrete mixes

| Mix Designation | M₁ | M₂ | M₃ | M₄ | M₅ | M₆ | M₇ | M₈ |
|-----------------|----|----|----|----|----|----|----|----|
| GWP, kg CO₂ eq  | 359.57 | 266.46 | 172.78 | 356.67 | 334.0 | 331.7 | 238.36 | 144.44 |
| Compressive strength (28 days), MPa | 55.8 | 40.2 | 24.0 | 45.0 | 51.9 | 42.0 | 32.8 | 21.0 |
| Compressive strength (180 days), MPa | 59.1 | 56.6 | 37.6 | 50.0 | 57.1 | 48.7 | 48.9 | 35.5 |
| CO₂ intensity (28 days), kg CO₂ MPa⁻¹ | 6.45 | 6.62 | 7.20 | 7.93 | 6.43 | 7.89 | 7.26 | 6.88 |
| CO₂ intensity (180 days), kg CO₂ MPa⁻¹ | 6.08 | 4.70 | 4.60 | 7.13 | 5.85 | 6.81 | 4.87 | 4.06 |

Figure 3: GWP values of concrete mixes for 1 m³ FU.

As discussed in section 2.1, selection of single FU is not desirable to assess the comparative impacts of concretes having diverse material characteristics. The volume of concrete is taken as the basic functional unit while calculating material requirement for the mix. However, volume cannot be taken as a sole unit in the environmental assessment of concrete. This is particularly important in cases of comparative assessment of two concrete mixes having different compositions and different characteristic properties. The studies at global scale have concluded that the 87-92% of carbon emissions through traditional concrete is attributed to CO₂ embodied with OPC binder in the mix. In first phase green concretes with SCMs, the replacement of OPC with SCMs is intended to reduce this embodied carbon. On a volumetric scale, it appears that there will be drastic decline in embodied carbon due to low emission factors of SCMs. However, these substitutions might not yield the concrete with functional properties at par with the compared traditional mix. Similarly, in case of second phase green concretes with aggregate replacements only, it appears that the change in embodied emissions would be negligible. This is basically due to low emission factor associated with the aggregates compared to cement and no relative difference in embodied emissions of replaced and virgin aggregates. However, such concrete might demand higher cement content.

To overcome this limitation, several recent studies have considered compressive strength at 28 days as an additional functional unit along with 1 m³ volume of concrete [3,7]. Damineli et al. [71] proposed
a generalized term called as CO₂ intensity \( (C_i) \), in kg-CO₂/m²/MPa to relate CO₂ emission with the compressive strength for any type of mix. It is given by equation (8):

\[
C_i = C_T / f'_c
\]

Where, and \( C_T \) is the total equivalent CO₂ emission of concrete (kg-CO₂/m³) as evaluated using LCA methodology and \( f'_c \) is the attained/targeted compressive strength at an age of 28 days (MPa). These normalized values of CO₂ emissions with respect to compressive strength is a representative term. It is adopted in many studies for a systematic and consistent comparison of EI for different mixes. This term \( C_i \) can be very effectively used to depict the environmental advantage/disadvantage of green concrete.

The values of \( C_i \) for all the mixes are found out based on compressive strength values at 28 days and 180 days and presented at Table 3. Figure 4 shows the variations of \( C_i \) with respect to 28 days and 180 days strength. It is evident from the results that the concrete with FA substitution of 60% present the maximum benefit when considered in relation to its strength development at 180 days. The mix M₃ depicts peculiar aspect of consideration of proper FU. If 28 days compressive strength is considered as FU, it can be seen that concrete with 60% FA presents \( C_i \) value higher than the normal concrete. It shows that the selection of functional unit is an important criterion in LCA analysis to get realistic conclusions.

![Figure 4: CO₂ intensity for concrete mixes.](image)

3. Carbon intensity of green concretes with SCMs- Literature findings and discussions

The studies in the literature presents environmental analysis of green concrete with different SCMs. The comparative analysis of concretes with different SCMs in a single study is presented by few researchers [7, 19, 38, 42, 43]. To obtain a general finding on comparative benefit of SCMs the \( C_i \) values are found out for the green concretes of which environmental assessment is performed in the literature. These results are obtained from 29 studies from peer reviewed journals available in the literature. Figure 3 presents a relationship between \( C_i \) and \( f'_c \) for these green concretes in comparison with traditional concrete. The findings of the researchers regarding the types and quantity of binders used, compressive strength values and corresponding CO₂ emissions are tabulated. These tabulated values are available at Appendix-A.

The best fit curves for this relationship for different binders are also presented at figure 5. The types of binders which are studied in minimum five studies are considered in this analysis. It is observed that the CO₂ intensity decreases as compressive strength increases which means high strength concrete emits less CO₂ to develop unit compressive strength. The value of \( C_i \) ranges from maximum value of 16.11 kg-CO₂/m³ MPa⁻¹ for 20 MPa strength OPC concrete to 4.61 kg-CO₂/m³ MPa⁻¹ for 73 MPa OPC+FA concrete. The best fit curves for different binders are in agreement with the conclusions derived by Yang et al. [51] that OPC+SCM concretes gives lower value of \( C_i \) for a given strength of concrete compared
to the concrete with only OPC binder. The OPC+GBFS mixes are seen to have lowest $C_i$ value at a given compressive strength.

![Figure 5: Relationship between compressive strength ($f'_c$) and carbon intensity ($C_i$).](image)

3.1 Effect of variations in system boundaries on LCA of concrete

Most of the LCA studies in the literature have used cradle to gate as the system boundary of assessment. The other stages of life cycle of concrete beyond the manufacturing stage also have a noticeable effect on the overall assessment of any EI. In case of carbon assessment of green concretes, LCA demands consideration of use/service life phase, demolition phase and reuse phase. The results from the literature clearly signifies the importance of these phases in life time carbon auditing of concrete.

Valipour et al. [72] states “A green concrete may have good durability against aggressive environment causing it to require less demolitions and renovations over a given life period.” Garcia Segura et al. [43] underlines the importance of consideration of service life to calculate the annual emission of concrete. Results from the study by Nath et al. [73] at table 5 confirms the advantage of using green concrete in marine exposure when service life is considered in the analysis.

| Parameter                         | OPC Concrete | 40% FA Concrete |
|-----------------------------------|--------------|-----------------|
| Concrete cover, mm                | 35           | 40              |
| Service life, yrs.                | 18           | 25              |
| CO$_2$ emission, kg-CO$_2$/m$^3$/yr | 19.18       | 10.76           |

Once the service life of structure is known, the carbon uptake can be estimated during the service life. The carbon uptake after the demolition stage is improved due to crushing and reusing the concrete on an exposed surface [43]. It is evident from the results at table 6 that about 47% of the emissions may be reabsorbed by carbonation during post use phase.

| Parameter                                      | Concrete with | 35% BFS | 50% BFS | 80% BFS | 20% FA | 35% FA |
|------------------------------------------------|---------------|---------|---------|---------|--------|--------|
| CO$_2$ emission at production, placement and demolition stage (%) | OPC           | 100     | 100     | 100     | 100    | 100    |
| CO$_2$ absorption at use stage (%)             | 22.5          | 19.1    | 18.5    | 10.6    | 21.2   | 21.7   |
| CO$_2$ absorption after demolition stage (%)    | 25.1          | 21.4    | 17.3    | 9.9     | 23.7   | 20.3   |

Table 5. Effect of service life on LCA, Nath et al. [73].

Table 6. Effect of carbon uptake on LCA, Garcia-Segura et al. [43].
The second phase green concretes containing RA show an additional saving in carbon emissions when avoided impacts are considered as a part of the system boundary of LCA. Knoeri et al. [74] confirms that if benefits from co-products of recycling process such as avoided transport to landfill sites, recovery of iron scrap etc. are included, the RA concretes may be environmentally favorite. Napolano et al. [75] and Turk et al. [50] also explains the importance of avoided impacts in the inventory of LCA of concrete.

3.2 Effect of allocation procedure on LCA

The selection of allocation procedure for byproducts as described at section 2.2.1 greatly influences the outcome of assessment. In a classical comparison for FA and GBFS, Chen et al. [57] has shown how upstream impacts may completely modify the outcome of LCA depending on allocation method. It is obvious that for no allocation, where SCM was considered as total waste, the impacts were reported lower than that of cement bound mix. An allocation of 12.4% and 19.4% for mass allocation and 1% and 2.3% allocation for economic consideration, was calculated for FA and GBFS respectively. No allocation scenario presented 25% lower values of impact, whereas mass allocation reported substantially higher values than impact from cement binder. Economic allocation reported a lower value of carbon emission due to lower allocation factors.

4. LCA research – Indian context

India ranks second in production and consumption of cement on global scale. It accounts for more than 7% of the global installed capacity. Considering the current consumption and future demand for cement in India, the environmental evaluation of concrete life cycle as a whole and cement manufacture in particular, is a key factor in national agenda of sustainable development. Looking at the quantum of research on LCA of concrete, the LCA studies in India are at infancy stage. Most of the European countries have already developed national databases prepared on the prevailing ecological, economic and social issues. Ecoinvent database is one of the most popular databases used worldwide which is entirely based on European context. The parameters used in preparation of such a database might not match the parametric inputs prevailing in India. Citations of the research findings from foreign contexts or use databases from other countries is the platform on which India is relying on date for LCA studies. The existing inventories and databases for energy demand and emissions are lacking the information related to emerging economies like India. It is a due season for Indian sustainability stake holders to have a national database, especially to tackle the environmental menace caused by second largest consumed material after water.

It is unjustified to use foreign context for LCA of concrete in India. Lack of efficiency in monitoring systems, no stringent protocols, non-uniform emission standards in manufacturing sector are some of the factors responsible for deviations in values in Indian subcontinent when considered on international scale. Thus, use of international databases for Indian context may lead to conservative results. The environmental evaluation of most carbon intensive material in concrete, that is, cement is enough to explain the deviation of Indian LCA process from other nations. These deviations can be summarized as below:

- In India, limestone is the main raw material in cement manufacture, there is no much use of other raw material such as clay, shale etc., like other countries.
- Most of the cement manufacturing industries in India are housed around limestone quarries, so they have a better control of optimization of composition in raw meal. Thus, there is a possibility of having environmentally efficient product.
- The cement plants in India use dry process of clinkerization unlike foreign countries.
- Use of electricity as energy source for manufacturing plants gives higher upstream impact due to coal burning for electricity generation.
- There is saving in energy requirement as alternative fuels in the form of industrial waste and biomass are used in Indian cement industry.
5. Conclusions
The manufacture of ‘Green concrete’ by utilizing recycled waste from industrial and construction sector is encouraged as a sustainability initiative against resource depletion and EI caused by traditional concrete. While the resource benefit assessment is manageable, the quantitative evaluation of the EI of such ‘Green concrete’ has been a mystery. The concept of LCA is a reliable methodology used to evaluate EI of concrete in last two decades. For better understanding of concept of LCA, the significance of each phase of analysis in context of concrete manufacturing is highlighted in this study.

Most of the studies on LCA of concrete have used cradle-to-gate system boundary. This study highlighted that cradle to gate system boundary limits the credibility of environmental information and the results may be biased leading to overestimation or underestimation of impacts. A systematic step by step procedure for estimation of carbon emission in terms of GWP is presented with due consideration to all the possible sources of carbon emission. A list of most popularly used database and software which are used worldwide for LCA is also presented.

Typical composition of a green concrete mixes incorporating SCM and RCA were presented and application of LCA methodology to the mixes was demonstrated as an example of evaluation.

To understand the carbon reduction potential of green concretes, the results from 29 studies across the globe were used. The importance of using an appropriate functional unit in LCA to compare two different concrete mixes was highlighted.

The relationship of CO$_2$ intensity ($C_i$) and compressive strength ($f'_c$) was plotted for the results in literature. The comparative plot clearly depicted the relative impact of different binders at a given value of $f'_c$. OPC concrete was observed to have highest $C_i$ value while GBFS blend was found to be beneficial over FA blend with reduced $C_i$ value.

This study focused a need of complete LCA of concrete which includes primary and secondary life of concrete. The importance of carbon uptake of concrete during usable life span and post demolition phase was highlighted with prominent findings from the literature. The other influential factors such as importance of FU, durability and service life, as well as effect of allocation method was discussed in the study.

The compatibility of LCA studies in concrete industry in Indian context was also discussed in the current study highlighting the sources of domestic deviations from rest of the world.

Supplement: Appendix A- Carbon intensity values for green concrete relative to compressive strength values for green concretes available in literature.

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APPENDIX- A

Data from selected studies for establishing relationship between Compressive Strength ($f'_c$) and Carbon intensity ($C_i$)

| Sr. No. | Author & Year     | Binder Composition (Kg/m³) | Compressive Strength ($f'_c$), MPa | CO₂ emission, Kg-CO₂/m³ | $C_i$ Value |
|---------|-------------------|----------------------------|----------------------------------|-------------------------|-------------|
| 1       | Nisbet et al., 2002 | OPC: 223, FA: 0, GBFS: 0 | 20                               | 228                     | 11.4        |
|         |                    |                            | 30                               | 279                     | 9.3         |
|         |                    |                            | 35                               | 329                     | 9.4         |
|         |                    |                            | 20                               | 199                     | 9.95        |
|         |                    |                            | 20                               | 188                     | 9.4         |
| 2       | Prusinski et al., 2004 | OPC: 223, FA: 0, GBFS: 0 | 20                               | 228                     | 11.4        |
|         |                    |                            | 35                               | 329                     | 9.4         |
|         |                    |                            | 50                               | 482                     | 9.64        |
|         |                    |                            | 20                               | 189                     | 9.45        |
|         |                    |                            | 20                               | 160                     | 8           |
|         |                    |                            | 20                               | 131                     | 6.55        |
|         |                    |                            | 35                               | 227                     | 6.49        |
|         |                    |                            | 35                               | 182                     | 5.2         |
|         |                    |                            | 50                               | 326                     | 6.52        |
|         |                    |                            | 50                               | 260                     | 5.2         |
|         |                    |                            | 70                               | 292                     | 4.17        |
|         |                    |                            | 70                               | 233                     | 3.33        |
| 3       | O’Brien et al., 2009 | OPC: 324, FA: 0, GBFS: 0 | 32                               | 320                     | 10          |
|         |                    |                            | 32                               | 293                     | 9.16        |
|         |                    |                            | 32                               | 286                     | 8.94        |
|         |                    |                            | 32                               | 278                     | 8.69        |
|         |                    |                            | 32                               | 270                     | 8.44        |
|         |                    |                            | 32                               | 253                     | 7.91        |
|         |                    |                            | 32                               | 278                     | 8.69        |
### APPENDIX- A

Data from selected studies for establishing relationship between Compressive Strength \( (f'_{c}) \) and Carbon intensity \( (C_i) \)

| Sr. No. | Author & Year     | OPC (Kg/m³) | FA (Kg/m³) | GBFS (Kg/m³) | Compressive Strength \( (f'_{c}) \), MPa | \( \text{CO}_2 \) emission, Kg-CO₂/m³ | \( C_i \) Value |
|---------|-------------------|-------------|------------|--------------|----------------------------------------|----------------------------------|--------------|
| 4       | Park et al., 2012 | -           | 0          | 0            | 32                                     | 278                              | 8.69         |
|         |                   | -           | 0          | 0            | 18                                     | 290                              | 15.48        |
|         |                   | -           | 0          | 0            | 21                                     | 325                              | 16.11        |
|         |                   | -           | 0          | 0            | 24                                     | 353                              | 12.71        |
|         |                   | -           | 0          | 0            | 27                                     | 378                              | 14           |
|         |                   | -           | 0          | 0            | 30                                     | 390                              | 13           |
| 5       | Proske et al., 2013 | 270         | 10         | 0            | 54                                     | 275                              | 11.19        |
|         |                   | 150         | 250        | 0            | 43                                     | 135                              | 5.09         |
|         |                   | 150         | 250        | 0            | 51                                     | 82                               | 1.61         |
| 6       | Jiang et al., 2014 | 225         | 0          | 0            | 20                                     | 230                              | 5.55         |
|         |                   | 335         | 0          | 0            | 35                                     | 340                              | 9.71         |
| 7       | Van den Heede and Belie, 2014 | 318         | 56         | 0            | 45                                     | 280                              | 6.22         |
|         |                   | 175         | 0          | 175          | 30                                     | 160                              | 5.33         |
|         |                   | 105         | 0          | 245          | 25                                     | 180                              | 5.22         |
|         |                   | 225         | 225        | 0            | 30                                     | 210                              | 1.77         |
| 8       | Celik et al., 2014 | 461         | 0          | 0            | 52                                     | 569                              | 10.94        |
| 9       | Crossin, 2015     | 112         | 0          | 262          | 32                                     | 198                              | 6.19         |
| 10      | Turk et al., 2015 | 320         | 0          | 0            | 43                                     | 260                              | 6.05         |
|         |                   | 240         | 80         | 0            | 43                                     | 195                              | 4.53         |
| 11      | Gettu et al., 2016 | 310         | 0          | 0            | 30                                     | 343                              | 11.43        |
|         |                   | 360         | 0          | 0            | 50                                     | 418                              | 8.36         |
|         |                   | 217         | 93         | 0            | 30                                     | 275                              | 9.17         |
APPENDIX- A

Data from selected studies for establishing relationship between Compressive Strength ($f'_c$) and Carbon intensity ($C_i$)

| Sr. No. | Author & Year                  | Binder Composition (Kg/m³) | Compressive Strength ($f'_c$), MPa | CO$_2$ emission, Kg-CO$_2$/m³ | $C_i$ Value |
|---------|--------------------------------|----------------------------|-----------------------------------|-------------------------------|-------------|
|         |                               | OPC FA GBFS                |                                   |                               |             |
| 12      | Gursel et al., 2016           | 266 114 0                 | 50                                 | 325                           | 6.5         |
| 13      | Tait and Cheung, 2016         | 380 0 156                 | 40                                 | 339                           | 8.48        |
| 14      | Van den Heede and Belie, 2017 | 350 0 0 266               | 45                                 | 315                           | 7           |
| 15      | Flower and Sanjayan, 2017     | 268 0 0                   | 25                                 | 290                           | 11.6        |
| 16      | Mohammadi and South, 2017     | 200 0 40 122              | 20                                 | 205                           | 10.25       |
| 17      | Kurda et al., 2018a           | 350 0 0 105               | 25                                 | 225                           | 9           |
| 18      | Miller, 2018                  | 180 288 0                 | 22                                 | 236                           | 10.73       |
## APPENDIX- A

Data from selected studies for establishing relationship between Compressive Strength ($f'_c$) and Carbon intensity ($C_i$)

| Sr. No. | Author & Year         | Binder Composition (Kg/m³) | Compressive Strength ($f'_c$), MPa | CO₂ emission, Kg-CO₂/m³ | $C_i$ Value |
|---------|-----------------------|-----------------------------|-----------------------------------|--------------------------|-------------|
|         |                       | OPC | FA  | GBFS |                            |             |
| 19      | Nath et al., 2018     | 308 | 132 | 0    | 45                         | 306         | 6.8        |
|         |                       | 264 | 176 | 0    | 66                         | 269         | 3.68       |
| 20      | Pillai et al., 2018   | 310 | 0   | 0    | 45                         | 335         | 7.44       |
|         |                       | 360 | 0   | 0    | 60                         | 380         | 6.33       |
| 21      | Marinkovic et al. 2010| 315 | 0   | 0    | 39                         | 308         | 7.9        |
| 22      | Faleschini et al., 2014| 310 | 0   | 0    | 35                         | 188         | 5.37       |
| 23      | Tosic et al., 2014    | 384 | 0   | 0    | 42                         | 364         | 8.67       |
| 24      | Jimenez et al., 2015  | 354 | 0   | 0    | 44                         | 334         | 7.59       |
| 25      | Serres et al., 2015   | 376 | 0   | 0    | 40                         | 381         | 9.53       |
| 26      | Fraj and Idir, 2017   | 350 | 0   | 0    | 43                         | 260         | 6.05       |
| 27      | Kleijer et al., 2017  | 280 | 0   | 0    | 35                         | 248         | 7.09       |
| 28      | Jimenez et al., 2018  | 350 | 0   | 0    | 37                         | 275         | 7.43       |
| 29      | Gursel and Ostertag, 2019 | 570 | 0   | 0    | 98                         | 754         | 7.69       |