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A Comparative Study of Energy Consumption, Global Warming Potential and Impact Categories of Four Different Blends of Concrete Using Cradle to Gate Life Cycle Assessment

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Abstract

The present study is a comparison of four different concrete mixes using 'cradle to gate' life cycle assessment. The aim is to obtain environmental impact, focusing mainly on criteria pollutants (CO, lead (Pb), PM10, NOx, SO_2, and volatile organic compounds), global warming potential, energy consumption, and impact categories like human health, ecosystem quality, and resources. Each concrete mix design has different binder combination. CONOPC contains ordinary Portland cement (OPC) as a binder. CONPPC has 27% Fly ash + 73% OPC while CON PSC has 47% ground granulated blast furnace slag (GGBS) + 53% OPC as a binder. CONGP has 100% fly ash as a binder without the use of cement. The comparative results show that all three concrete mixes, i.e., CONPPC, CONPSC, and CONGP, performed better than CONOPC in terms of harmful gas emissions, energy use, and GWP. Further, with respect to three impact categories, CONOPC has the highest score with 11.06 pt and CONGP has the lowest score with 1.68 pt. CONPPC shows a reduction by almost 30% with a value of 7.77 pt whilst CONPSC shows an even further reduction by 46% with a value of 5.95 pt compared to CONOPC. It is recommended that OPC cement should be replaced by either Portland slag cement (PSC) or Portland pozzolana cement (PPC) in concrete production. Geopolymer concrete is also a good substitute for traditional concrete. Recommendations from this work would assist concrete producers to choose the best available options without compromising the performance of concrete while reducing the negative environmental impact during production.

Keywords: - Life cycle Assessment (LCA), Ground Granulated Blast Furnace Slag (GGBS), Fly Ash (FA), Geopolymer concrete, Portland Pozzolana Cement (PPC), Portland Slag Cement (PSC).

1.0 Introduction

The construction sector is one of the leading sectors for material utilization worldwide. Approximately 20% of materials across the world are utilized in India, and concrete is the most consumed one (Sandeep S et al. 2011). To meet this demand, gigantic cement production is done every year. Around 334.37 million tons of cement were produced in the year 2019–20 in India. Such high demand and production of cement are increasing the emission of harmful gases, as cement is responsible for 7% of global anthropogenic CO_2 emissions (A report by bureau of energy efficiency, government of India, 2015). In addition to this, natural aggregate extraction is responsible for ecosystem destruction through erosion. Further, wastewater and waste sludge emitted from the concrete batch plant can have harmful impacts on the water ecosystem (Guidelines on environmental management of c & d wastes, 2016). Therefore, it is essential to make modifications to concrete mixes to reduce negative environmental impacts and increase sustainability without compromising their performance and cost of production. Environmental impact can be reduced by replacing natural aggregates with recycled aggregates. For instance, to investigate the environmental impacts of copper slag and its alternative use as natural sand in high strength concrete application, a life cycle approach was applied by Aysegul Petek Gursel and Claudia Ostertag, (2019). Bruno Estanqueiroa et al., (2016), A.L.Kleijer et al., (2017), and Zhanggen Guo et al., (2018), studied the replacement of natural aggregates with recycled aggregates, and it was observed that the replacement of natural aggregates with recycled aggregates significantly reduces the environmental impact. It was observed by Brun Estanqueiroao et al. (2016), Janez Turk et al. (2015), Michael Tait et al.,(2016) and Yazdanbakhsha et al., (2019) that transportation distance from the quarry to the manufacturing plant and the source of energy used for manufacturing raw materials itself play a major role. The increase in transportation distances will lead to more fuel and energy use during transportation and may contribute to air pollution during the same. Environmental performance can be drastically improved by using renewable electricity instead of fossil fuel electricity (Chrystalla Chrysostomou et al.,2015) The Indian cement industry uses 97% of coal for energy generation during pyroprocessing, which results in higher energy consumption and GWP compared to the US, where 64% of coal is used during pyroprocessing (A. Petek Gursel et al.,2014).

Another way of achieving environmental sustainability is to replace the cement with mineral additives partially or fully. There is little scope for reducing CO_2 emissions without the use of secondary cementitious materials (SCM) like FA and GGBS (Leon Black, 2014). Hence, researchers have attempted to utilise such SCMs with partial or full replacement of cement. Flyash (FA) is a fine powder generated from the burning of coal in power stations whose composition may vary widely depending on the type of coal burnt and the condition of furnace firing. FA is a pozzolanic material that contains little calcium. FA can also reduce the need for natural aggregates as well as cement. Portland pozzolana cement (PPC) is a mixture of FA (15 to 35%) and OPC (Report on blended cement – 2022). Ground granulated blast furnace slag (GGBS) is a byproduct obtained during the separation of iron from the iron ore in blast furnaces in the steel manufacturing industry. Portland Slag Cement (PSC) is a mixture of blast furnace slag (up to 70%) and OPC. By substituting fly ash or blast furnace slag for portland cement, one can reduce the need for portland cement, which emits a lot of greenhouse gases during the pyroprocessing process (Report on blended cement – 2022), and it has been supported by previous studies. Michael W. Tait and Wai M. Cheung (2016) investigated three cement mixes: 100% OPC content, 35% FA replacement, and 70% GGBS replacement, with a primary focus on CO_2 emissions of three concrete mixes, performed using SimaPro 8 software and the ecoinvent database. It was concluded that replacement with GGBS produces lower CO_2 emissions than FA due to the possibility of a high percentage replacement of OPC. Ghasan Fahim Huseien and Kowk Wei Shah (2020) compared six concrete mixes with different percentages of fly ash (30, 40, 50, 60, and 70%) in place of granulated blast furnace slag

(GBFS) in a self-compacting concrete. It was observed that concrete with FA of 50% and above showed a reduction in CO_2 emissions by about 20% or above and energy consumption almost lower by 18%. The study done by Radhakrishna G. Pillai et al. in (2018) highlights the importance of the SCMs in terms of total energy consumption and carbon dioxide emissions. The study also suggests that the use of high grades of concrete can give better benefits to the SCMs. During these LCA studies, emissions only from the processing of GGBS and FA during the production of concrete are considered as both are the byproducts of industrial processes. Aysegul Petek Gursel et al., replaced OPC with Fly ash, rice husk ash and limestone flour by different percentages and concluded that with increasing percentage of SCMs GWP and air pollutants decreases (2015).

Apart from these studies where cement was replaced partially, recent studies have also focused on the LCA of alkali activated concrete or geopolymer concrete, where cement is not used at all. Geopolymer materials are a mixture of natural or synthetic pozzolanic solids, activated with alkaline solutions such as sodium hydroxide and sodium silicate (T E McGrath et al.2018). This paste acts as a binder to replace OPC. Common geopolymer materials are FA and silica fume. It has been observed that carbon dioxide emissions can be reduced by up to 90% by replacing cement fully, because the majority of CO_2 is produced during cement pyro processing (M. I. Abdul Aleem et al, 2012). The study done by Rishbh Bajpal et al. in (2020) represents the LCA of geopolymer concrete containing fly ash and silica fume, in which a case study of Jaipur city is taken for transportation of raw materials and cost analysis. It is concluded that fly ash and alkaline activators are major sources of CO_2 emissions in the case of geopolymer concrete. The GWP of geopolymer concrete is lower than that of conventional concrete. The geopolymer concrete activated without sodium silicate has the lowest environmental impacts. It was also observed that the source of alkali activators and energy mix affects the LCA results, using NaOH made from solar salt can reduce environmental impacts. (Daniel A. et al.2018).

From the literature survey, it was observed that very limited attempts were made to compare different types of concrete mixes with different cement blends using LCA. Furthermore, most studies rely on commercial software tools (e.g., GaBi, Simapro, or openLCA) based on the database that belongs to a particular region. It is important to find out the environmental impact based on the data related to the region under study and collected directly from the manufacturer. Hence, the present study focuses on the cradle to gate life cycle assessment of four different concrete mixes with different cement blends; CONOPC, CONPPC, CONPSC, and CONGP; based on the data collected from the ready-mix concrete plant directly as explained in the subsequent section of this paper. A cradle to gate analysis of all four mixes has been done using the "Green Concrete LCA webtool" (Life-Cycle Assessment of Concrete: Decision-Support Tool and Case Study Application,2014). Impact indicators and categories are then calculated by using the Eco-indicator 99 method.

2.0 Methodology

2.1 Background

Concrete mix designs can be made with different cementitious blends to enhance sustainability and reduce negative environmental impacts. In the present study, each mix design has a different binder combination; CONOPC contains traditional OPC cement as a binder.

CONPPC has 27% FA + 73% OPC while CONPSC has 47% GGBS + 53% OPC as a binder. The mix design has been done according to IS 456:2000 and as per IS 10262-2009, all having a fix cementitious content of 345 Kg/m$^{3.}$ The last mix, CONGP, contains a paste of FA with alkali activators without cement. Natural aggregates were used for all four concrete mixes. The data for the first three has been collected from a ready-mix concrete plant situated at Rajkot, Gujarat, India. The data related to cement manufacturing and processing has been collected from the plant situated in Kutch district, Gujarat, from where cement is supplied to the ready-mix concrete plant under consideration. The design of the CONGP has been done in the laboratory of Marwadi University, Rajkot, Gujarat. The transportation distances for raw materials have been considered the same as in the case of the first three, to know the CONGP's negative impact on the environment. Assumption has been made that it had been manufactured at the same ready mix concrete plant as that of the first three concrete mixes. The design grade of all three concrete was M20. The mix design of all four concrete mixes is shown in Table 1. The details of cement production are shown in Table 2.

A cradle-to-gate LCA of these four mixes has been done. Energy consumption, Global warming potential (GWP) and air pollutant emissions of all concrete mixes are calculated using the "Green Concrete LCA webtool" developed by Petek Gursel (Life-Cycle Assessment of Concrete: Decision-Support Tool and Case Study Application, 2014). This tool allows users to enter variations of concrete mix designs that can be applied to different construction projects with different geographical locations and production technologies, as well as electricity generation and transportation options worldwide. Entering details related to the geographical location under study may not be possible in other cases where different software or tools are used. As these data vary from region to region, using data that has already been fed into the software may not produce accurate results for the region under study. In the present study, data related to energy use and electricity grid mix associated with processes like quarrying and processing of raw materials, coarse and fine aggregates, and SCMs are taken from the report produced by the central electricity authority of India (Installed capacity report, 2022). The data related to fuel used during the process of pyro processing phase has been collected from a report produced by the bureau of energy efficiency, ministry of power, government of India (2015).

The harmful gases are characterized into different impact categories using the Eco- indicator 99 method. This method is a modified version of the Eco- indicator 95 method, developed by Pre consultants (2001). Human Health (Unit: DALY Disability adjusted life years), Ecosystem Quality (Unit: PDF*m^{2}yr; PDF= Potentially Disappeared Fractions of Plant species), and Resources (Unit: MJ surplus energy) are three damage categories that are analyzed by allocating various emissions to impact categories. Damage to human health expresses the number of years of life lost and the number of years lived disabled due to pollutants. Damage to ecosystem quality expresses the loss of species over a certain area and during a certain time, while damage to resources expresses the surplus energy needed for future extractions of minerals and fossil fuels. As all three damage categories have different units, results are normalized to make these values dimensionless and comparable. The normalisation factors express the total impact occurring in a reference region within a reference year. The normalised values are again multiplied by the weighting factors to understand the relative importance of each impact category.

2.2 The Life Cycle Assessment (LCA) approach

Life Cycle Assessment (LCA) is a methodology to assess the environmental impact of a product, process, or service, right from the extraction of the raw materials to the disposal of the same at the end of the utility period (ISO14040, 2006). To compare concrete mix designs, a cradle to gate approach is applied. The hypothesis of the present study is that negative environmental impacts can be reduced by an increasing percentage of SCMs. The analysis is done in two stages, i) the cement production stage and ii) the concrete production stage. Calculation and analysis are done separately for both the stages, each process wise, to know the most harmful process and stage of the production. The outline of LCA for the four concrete mix designs is as follows:

i) Goal and scope definition: The functional unit and system boundary of the study are defined at this stage. The functional unit for the study is kept as one cubic meter (cum) of concrete with respect to strength, i.e.1 cum of concrete with the same strength will be compared for various blends of concrete. As concrete is a predominant construction material used in the construction industry, it is important to check the performance of concrete with respect to strength and durability. Comparison between different blends of concrete would be more accurate when it is done for the same strength rather than just doing it for the same volume (ISO14040, 2006).

ii) Inventory analysis: This stage entails compiling and quantifying the inputs throughout the concrete mix design life cycle by feeding data into the selected analysis tool for each material and process as per system boundary. The calculation of tabulated numerical values in terms of inputs and outputs with respect to the environment for various processes is done. The collected data is shown in Tables 1,2 and 3.

iii) Impact assessment: In this stage of LCA, the magnitude and significance of the environmental impacts of each mix design throughout its life cycle are evaluated. The significance of the collected data and how it affects the various outcomes are also determined.

iv)Interpretation: Concrete mix designs will be compared in terms of harmful gas emissions, GWP, energy use, and impact categories. The best options in terms of achieving sustainability in the concrete production industry will be highlighted.

2.2.1 System Boundary

The system boundary (Fig.1 and 2) includes all of the necessary inputs, which starts from raw material extraction, transportation, and ends with the production of concrete. The system boundary does not include emissions related to SCM production as GGBS and FA are byproducts of steel and electricity industries, and hence their impacts are not directly related to the concrete production. For this assessment, only processing and transportation emissions are allocated to these materials. Also, impact indicators and damage categories are calculated based on air emission data only. Emissions to water and soil are not considered in this study.

2.3 Concrete mix designs

The four concrete mix designs undergoing LCA are summarized in Table 1. Following observations are made for all four mixes:

i) The concrete grade for all four mixes is kept constant at 20 megapascals (MPa).

ii) The water/cement ratio of CONOPC, CONPPC, and CONPSC is kept at 0.35, whereas the water/paste ratio is 0.39 in the case of CONGP.

iii) The binder content is 345 Kg/m^3 for the first three concrete mixes but is reduced to 300 Kg/m^3 for the fourth concrete mix to meet IS code requirements and keep strength and water-cement ratio nearly equal.

iv) In order to ensure production of 1 m^3 of concrete, there is a slight variation in mass and density across all four mixes, as shown in Table 1.

Fig.1 System boundary for cement production stage

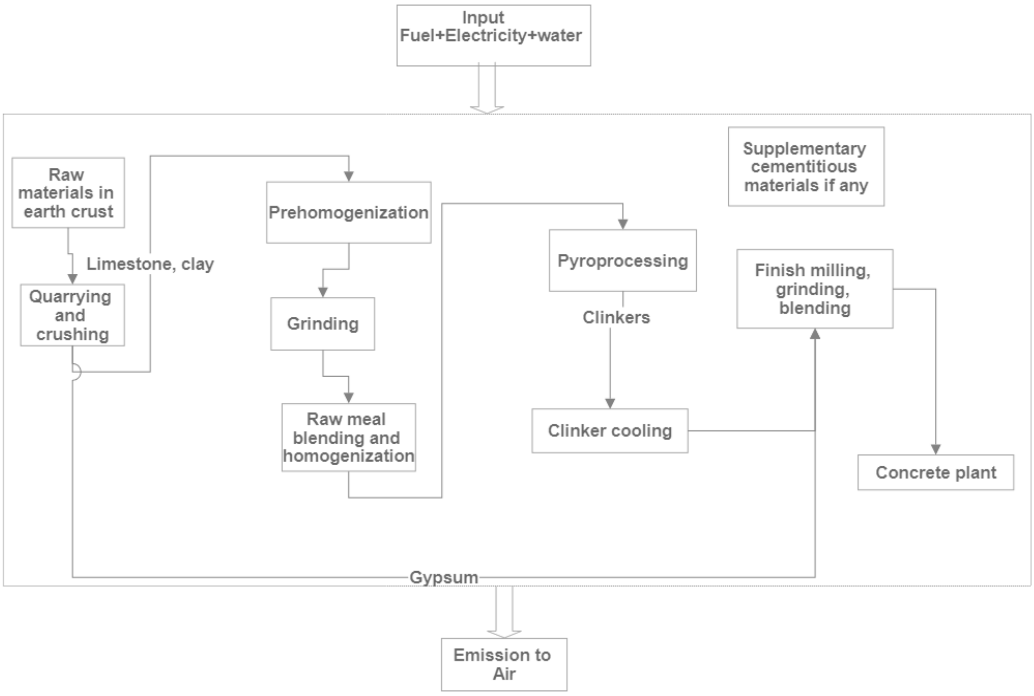

Fig.2 System boundary for concrete production stage

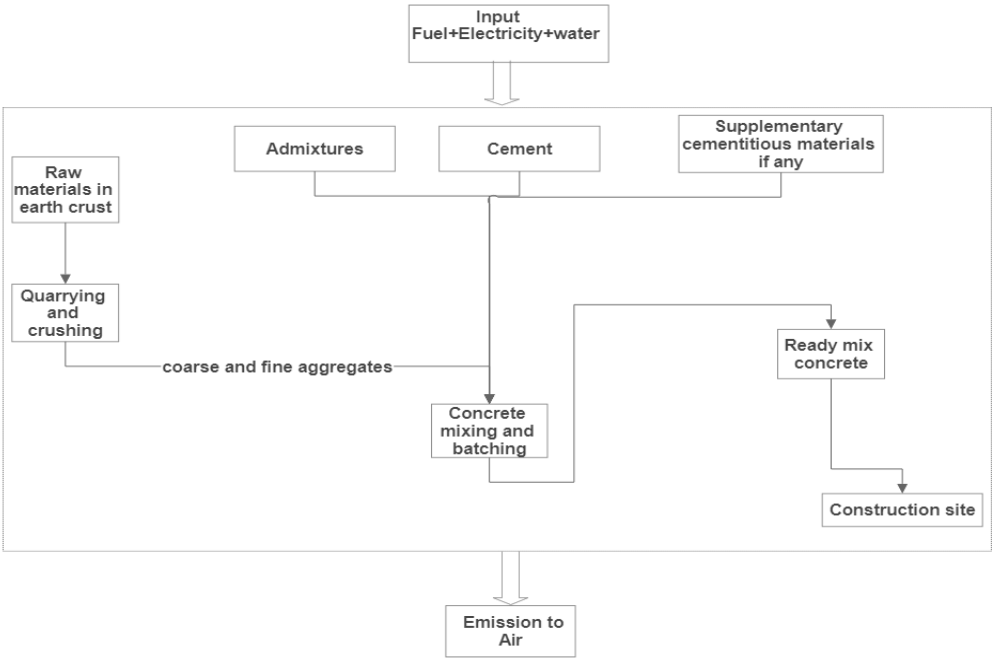

Table 1 Material requirement for mix design of concrete

Material	**Quantity per cum of concrete (Kg/m^3)**			
	CONOPC	**CONPPC**	**CONPSC**	**CONGP**
Cement	345	250	181	-
Fine aggregates (sand)	688	648	648	727
Coarse aggregates	1211	1231	1251	1351
Water	120	120	120	118
Fly ash in concrete	-	-	-	300
Plasticizers	4	3	2	-
Accelerating admixtures				
NaOH	-	-	-	20
Na_2SiO_3	-	-	-	26
Total cementitious material	345	345	345	300
Total weight of concrete	2368	2347	2366	2542
Water/binder ratio	0.35	0.35	0.35	0.39

Table 2 Details of cement production

Details of materials	**Quantity per cum of concrete (Kg/m^3)**			
	CONOPC	**CONPPC**	**CONPSC**	**CONGP**
Cement clinkers	328	238	172	-
Gypsum	17	12	9	-
Flyash blended in cement	-	95	-	-
GGBS blended in cement	-	-	164	-

Table 3 Inventory data collection

1. Transportation input	**Distance travelled in Km (by truck)**			
	CONOPC	**CONPPC**	**CONPSC**	**CONGP**
Cement raw materials to cement plant	5	5	5	-
Gypsum to cement plant	960	960	960	-
Flyash to cement plant	-	59	-	-
GGBS to cement plant	-	-	140	-
Fine aggregates to concrete plant	57	57	57	57
Coarse aggregates to concrete plant	32	32	32	32
Cement to concrete plant	370	370	370	-
Flyash to concrete plant	-	-	-	240
Admixtures to concrete plant	20	20	20	20
2) Cement production phases	**Product**		**Technology**	

Storage and PR homogenization of raw material	Raw Meal	Dry process raw storing, non pre blending
Grinding of raw material	Ground Meal	Dry raw grinding, ball mill
Raw meal homogenization	Blend Meal	Raw meal homogenization, blending and storage
Pyro processing	Clinker	Kiln- calcinations
Clinker cooling	Cooled clinker	Reciprocating cooler
Milling, grinding, blending and packing	Traditional OPC	Ball mill

3) Details of fuel use for pyro processing (A report by Bureau of Energy Efficiency, Government of India, 2015)

Fuel	**% by Energy source**
Pulverized coal	97.49
Petcock	2.51

4) Conveying Technology

Product of each face	**Conveyance mode**
Raw Meal	conveyer belt
Ground Meal	bucket elevator
Blended Meal	conveyer belt
Clinker	conveyer belt
Clinker cooled	Bucket elevator

5) Concrete plant technology

Batching Plant PM Control Technology	Controlled Fabric filter
Mixing/loading concrete material in truck	Mixer loading

6) Details of Electricity Grid mix during Production (Installed capacity report, 2020)

Contribution of Electricity source	**%**
Coal	53.7
Lignite	1.7
Gas	6.7
Diesel	0.1
Nuclear	1.8
Large Hydro	12.3
Small Hydro	1.3
Wind Power	10.2
Solar Power	9.5
Biomass	2.7

3.0 Life cycle assessment results:

Results were obtained by using the Green Concrete LCA webtool and the Eco-indicator 99 impact assessment method. For the analysis and quantification of the environmental impacts of processes, The analysis and quantification of environmental impacts of the processes is based on the input of resources (concrete and cement materials), primary energy use (in the form of fuel and electricity), as well as outputs of air emissions due to use and transportation of these resources. Results are presented in the form of criteria pollutants (CO, Pb, PM10, NOx, SO_2), volatile organic compounds (VOC), Global warming potential (GWP), and energy consumption during each phase of concrete production. Furthermore, each criteria pollutant is allocated to the relevant impact categories, which are then grouped together to form damage categories, human health, ecosystem quality, and resources. The input for concrete production includes the extracted raw materials like gypsum, limestone, sand and gravel and industrial byproducts like FA and GGBS. The quantities of these raw materials are identified in inventory analysis. Due to lack of availability of data the resource use for admixture production is not considered in the tool. The results are presented in three parts: criteria pollutants, Energy consumption and GWP and impact categories.

i) Criteria Pollutants:

The total pollutant emissions for all four concretes is shown in Table 4 and compared in Fig.3. It is clear from the analysis that maximum carbon monoxide (CO) is emitted in the case of CONOPC, followed by CONPPC and CONPSC, whilst it is almost zero in case of CONGP. There is a considerable reduction in CO emissions by almost 12% in the case of CONPPC compared to CONOPC, and a reduction of 21% is observed in the case of CONPSC. Similar results are observed in case of Lead. When compared to CONOPC, CONPPC results in a nearly 9% reduction in NOx emissions, while CONPSC results in a 15% reduction. A reduction of almost 27% is observed in the case of CONGP with respect to CONOPC. Overall CONOPC is the highest emitter of air pollutants and CONGP is the lowest one, except for PM10, where PM10 emission is almost equal for CONPPC, CONPSC, and CONGP. The emission of air pollutants in the case of CONGP is primarily attributed to two ingredients: FA in concrete and accelerating admixtures, as the amount used in this case is the highest compared to the other three concrete mixes.

ii) Energy consumption and GWP:

The energy consumption and GWP are one of the main environmental impacts analyzed throughout the production and transportation. The results are presented in Fig.4-5, and Table 5. Energy consumption and GWP are the highest during the accelerating agent phase of concrete production in the case of CONGP compared to the other three mixes due to more amount used compared to other three mixes. Also, energy consumption for CONGP during fine aggregates processing is 5% higher than CONOPC and 11% higher than CONPPC and CONPSC because of more quantity use. Similarly, GWP is higher in case of CONGP by 5% than CONOPC and 14% than CONPPC and CONPSC during fine aggregates processing as shown in Table 5. Quantity of coarse aggregates is more in case of CONGP followed by CONPSC and CONPPC than CONOPC, energy consumption and GWP for the coarse aggregate processing phase is lowest in case of CONOPC as shown in Table 5. For all other phases, CONGP is the lowest emitter. In the case of the first three concrete mixes, energy use and GWP are highest during the process of pyro processing of cement. It is less in the case of CONPSC compared to CONOPC and CONPPC, as a greater percentage of cement has been replaced by GGBS than in the case of CONPPC. Altogether, CONOPC is the highest contributor to energy consumption and GWP, as shown in Fig. 6.-7. It can be observed that there is a considerable reduction in energy consumption and GWP in the cases of CONPPC, CONPSC, and CONGP compared to CONOPC. Energy consumption is reduced by 20% in the case of CONPPC, 24% in the case of CONPSC, and 30% in the case of CONGP compared to CONOPC. Similarly, GWP is reduced by 25% in the case of CONPPC, 40% in the case of CONPSC, and 75% in the case of CONGP compared to CONOPC. Similar results were observed by Rishabh Bajpai et al (2020) in case of geopolymer concrete where reduction in GWP is observed up to 75%.

Table 4 Air pollutants from cement and concrete production stages

Concrete Mix	**CO (Kg/cum)**	**Lead (Kg/cum)**	**NOx (Kg/cum)**	**PM 10 (Kg/cum)**	**SO_2 (Kg/cum)**	**VOC (Kg/cum)**
CON OPC	107.671	0.016	1.427	0.128	0.904	0.014
CON PPC	78.113	0.012	1.081	0.111	0.687	0.011
CON PSC	56.616	0.009	0.847	0.1	0.564	0.008
CON GP	0.157	0	0.407	0.102	0.222	0.002

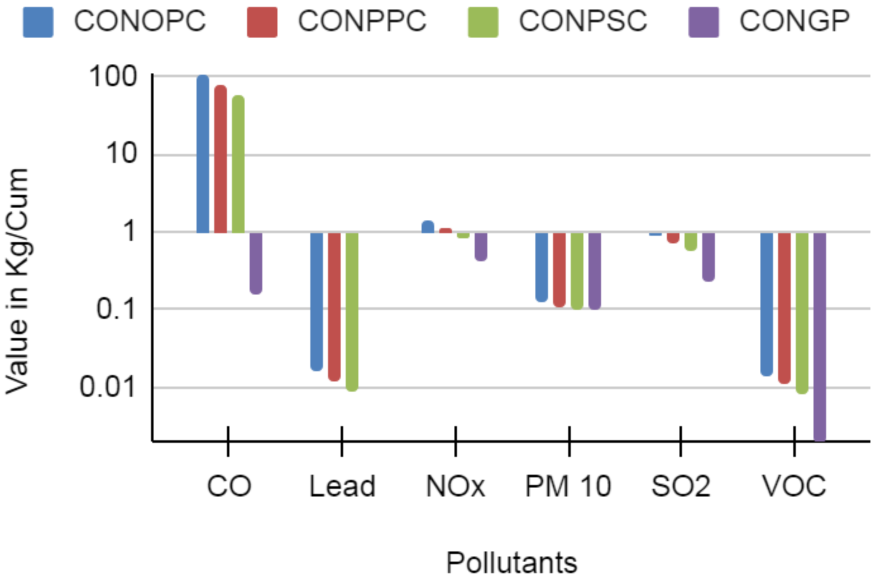

Fig.3 Comparison of Pollutant emissions

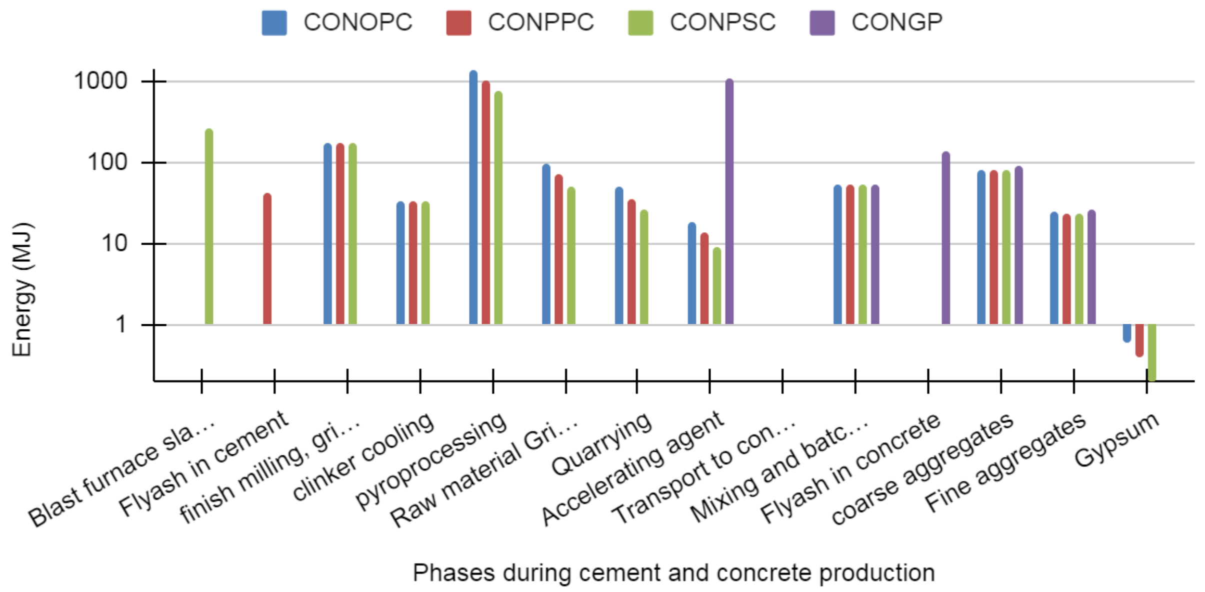

Fig.4 Energy consumption during various phases of cement and concrete production

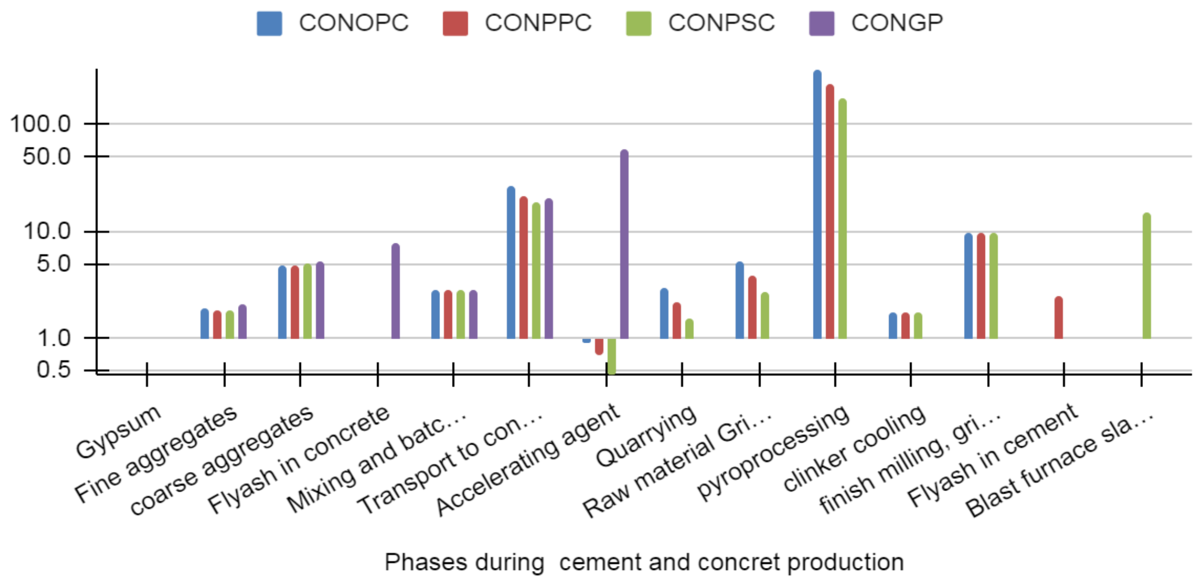

Fig.5 GWP during various phases of cement and concrete production

iii) Impact indicators and categories:

Air pollutants are classified into damage indicators like respiratory organics, respiratory inorganics, ecotoxicity, eutrophication/acidification, and fossil fuels, which are divided into three impact categories such as human health, ecosystem quality, and resources as shown in Table 6. CO, NOx, SO_2 and PM10 are allocated to the impact indicator respiratory inorganics and VOC is allocated to respiratory organics, and they are all combined for the impact category human health. Like so, lead, NOx, and SO_2 are allocated to the impact category of ecosystem quality (The Eco Indicator 99-A damage PreConusltnats 2001). For the impact category resources, energy from coal used during cement pyroprocessing is considered and, hence, overall impact is higher than the other two categories. The amount of air pollutants for all concrete mixes is multiplied by the damage factor shown in Table 6. in order to get the characterisation value of each pollutant. These values are then divided by the normalised damage factor, and further, these normalised values are multiplied by the weighted damage factors shown in the Table 8, impact category wise. Tables 7-8, and Figs. 8-10 summaries the findings.

For all three impact categories, CONOPC has the maximum value and CONGP has the lowest. The normalisation result shown in Fig. 8 illustrates the values of impact indicators with respect to each air pollutant. It is observed that though the emission value of NOx is less than that of CO in all cases, the impact is higher in the case of the impact indicator, respiratory inorganics, because of the high value of the damage factor, as shown in Table 6. This indicates that NOx is very harmful air pollutant to human health. The direct effects of NOx on human health are headaches, chronically reduced lung function, breathing problems, eye irritation, and loss of appetite (Jakub Krzeszowiak et al.,2016). NOx also damages ecosystem as shown in the next impact indicators: acidification and eutrophication.

Fig.9 illustrates the weighing values of each impact indicator, which is the product of normalisation results and weighting factors, which displays the relative importance of each impact indicator. Respiratory inorganics and fossil fuels show the highest importance in terms of impacts, followed by respiratory organics, acidification/eutrophication, and ecotoxicity. Table 8 illustrates the total weighted value of each impact category, which indicates that maximum damage is done to human health due to air pollutants emitted during various stages of cement and concrete production, followed by impact category resources for all four concrete mixes. It is maximum in the case of CONOPC and minimum in the case of CONGP. In the case of CONGP emission and energy use during thermal curing of concrete, has not been considered here and hence the value for impact indicator resources is zero. These values could be more if the thermal curing stage is considered. The value of the impact category ecosystem quality is negligible in all four cases. Fig.10 illustrates the total value of all impact categories as single score. CONOPC has the highest score with 11.06 pt and CONGP has the lowest score with 1.68 pt. The unit pt is dimensionless and its purpose is to compare relative differences between the concrete mixes. CONPPC shows a reduction by almost 30% with a value of 7.77 pt whilst CONPSC shows an even further reduction by 46% with a value of 5.95 pt compared to CONOPC. A reduction of almost 85% is observed in the case of CONGP. Single scores were formed from the weighted results and are attributed to each concrete mix. The similar results were observed by Michael W Tait, and Wai M Cheung (2016) while doing comparative life cycle assessment of three concrete blend; 100% OPC contain, 65% OPC content and 35% flyash content and 30% OPC and 70% GGBS mixes compared by simapro software and Eco indicator 99 method. The single score obtained for mix 1 was 13.9 pt, for mix 2 it was 10.8 pt and for mix 3 it was 8.52 pt.

Table 5 Energy use and GWP during various phases of cement and concrete production

Phases during cement and concrete production	**Energy(MJ)**				**GWP100 (Equivalent to CO_2)**			
	CON OPC	CON PPC	CON PSC	CON GP	CON OPC	CON PPC	CON PSC	CON GP
Gypsum	0.6	0.4	0.2	0.0	-	-	-	-
Fine aggregates	25.0	23.5	23.5	26.4	2.0	1.8	1.8	2.1
coarse aggregates	79.7	81.1	82.4	89.0	4.8	4.9	4.9	5.3
Flyash in concrete	0.0	0.0	0.0	135.0	0.0	0.0	0.0	7.8
Mixing and batching	53.4	53.4	53.4	53.4	2.9	2.9	2.9	2.9
Transport to concrete Plant	-	-	-	-	26.4	21.6	18.4	20.2
Accelerating agent	18.4	13.8	9.2	1063.2	0.9	0.7	0.5	58.8
Quarrying	49.5	35.9	26.0	0.0	3.0	2.2	1.6	0.0
Raw material Grinding	98.0	71.1	51.5	0.0	5.3	3.8	2.8	0.0
pyroprocessing	1416.4	1027.2	743.9	0.0	331.6	240.5	174.2	0.0
clinker cooling	33.0	33.0	33.0	0.0	1.8	1.8	1.8	0.0
finish milling, grinding, blending	177.6	177.6	177.6	0.0	9.6	9.6	9.6	0.0
Flyash in cement	0.0	42.7	0.0	0.0	0.0	2.5	0.0	0.0
Blast furnace slag in cement	0.0	0.0	271.4	0.0	0.0	0.0	14.9	0.0
Total	1951.6	1559.7	1472.2	1366.9	388.2	292.2	233.3	97.0

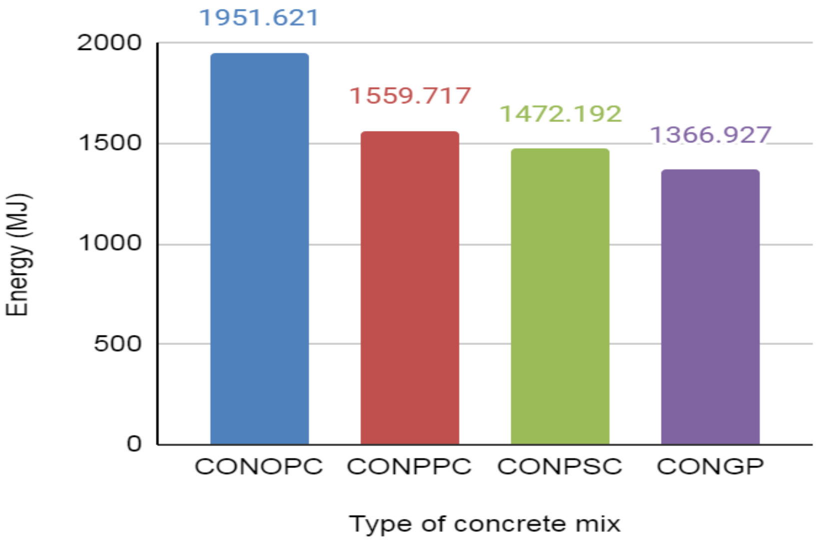

Fig. 6 Total Energy Consumption

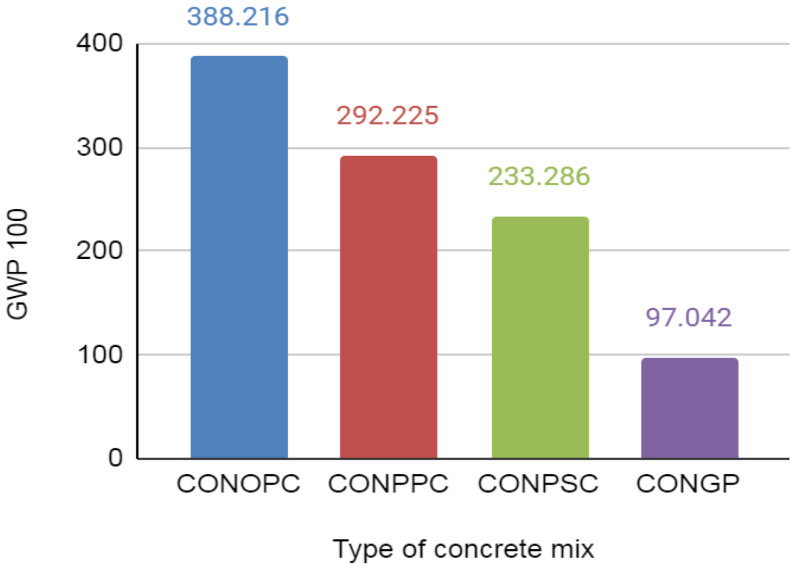

Fig.7 Total GWP produciton

4.0 Discussion and Recommendations

The results obtained from this work would help the concrete manufacturers to define the available options for concrete mix design. In this study, the material variation in each mix is the different cementitious blends, and hence recommendations can be made based on the cementitious materials. In the case of CONOPC, Portland cement is more readily available than FA and GGBS, and hence the manufacturer prefers to use it. Also, Portland cement is specially manufactured for construction purposes, unlike FA and GGBS, which are byproducts of industrial processes and sometimes availability may become an issue. But looking into the results of the life cycle assessment of the present study, it is strongly recommended that use of OPC should not be preferred just because of its ease of availability while overlooking the disadvantages from an environmental point of view. The obtained results clearly show that energy consumption can be reduced by 20%, 24%, and 30%, respectively, by using CONPPC, CONPSC, and CONGP in place of CONOPC per cubic meter of concrete production. It is also observed that GWP is reduced by 25%, 40%, and 75% in the cases of CONPPC, CONPSC, and CONGP, respectively. CONOPC has higher single scores in all three impact categories: human health, ecosystem quality, and resources. The value of a single score almost decreased by 30%, 46%, and 85% in the cases of CONPPC, CONPSC, and CONGP, respectively, than CONOPC. CONPPC does show a considerable reduction in energy use, GWP, and single score of all impact categories compared to CONOPC, but it is still less than CONPSC. The reason is that PPC can only contain a maximum of 35% FA addition (IS1489-1,1991) whereas PSC can contain a maximum of 70% of GGBS (IS455,1989). As explained earlier, CONGP shows the maximum advantage. The option can be definitely considered and taken forward. The only disadvantage with CONGP is that large-scale production of it in day-to-day application is difficult due to limitations like thermal treatment curing, which is likely to cause hazards and also increase the cost significantly. The study recommends that CONOPC should be replaced by CONGP to achieve maximum sustainability, wherever it is feasible from the point of view of manufacturing and cost. Otherwise, CONPSC is recommended very strongly, as it does not have any special manufacturing requirements and shows very promising results for improving the sustainability of concrete production. Apart from CONOPC, all other concrete mixes contain either FA or GGBS, which are waste materials and may otherwise be sent to landfill. It is also recommended that cement plants should choose waste materials based on the availability nearby, as this reduces fuel consumption and air pollutant emissions during conveyance.

Table 6 Characterisation of air pollutants to impact indicator and impact categories (Eco indicator 99 method, PreConusltnats 2001)

Impact category	Impact Indicator	Air Component	Damage Factor	Normalised damage factor	Weighted damage factor
Human Health (DALY)	Respiratory inorganics	CO	7.31E-07	1.55E-02	3.00E+02
		NOx	8.91E-05		
		SO_2	5.46E-05		
		dust (PM 10)	3.75E-04		
	Respiratory organics	VOC	6.46E-07		
Ecosystem quality(PDF*m2yr)	Ecotoxicity	Lead	2.40E-07	5.13E+03	5.00E+02
		NOx	4.60E-05		
	Acidification/ Eutrophication	SO_2	6.40E-05		
Resources (MJ surplus/MJ)	Fossil fuels	Energy from coal (cement pyroprocessing)	6.96E-02	5.94E+03	2.00E+02

Table 7 Normalized value of impact category for all concrete mixes

Impact category	Impact Indicator	Air Component	CON OPC	CON PPC	CON PSC	CON GP
Human Health	Respiratory inorganics	CO	5.08E-03	3.68E-03	2.67E-03	7.40E-06
		NOx	8.20E-03	6.21E-03	4.87E-03	2.34E-03
		SO_2	3.18E-03	2.42E-03	1.99E-03	7.82E-04
		dust (PM 10)	3.10E-03	2.69E-03	2.42E-03	2.47E-03

	Respiratory organics	VOC	5.83E-07	4.58E-07	3.33E-07	8.34E-08
Ecosystem quality	Ecotoxicity	Lead	7.49E-13	5.61E-13	4.21E-13	0
	Acidification/ Eutrophication	NOx	1.28E-08	9.69E-09	7.59E-09	3.65E-09
		SO_2	1.13E-08	8.57E-09	7.04E-09	2.77E-09
Resources	Fossil fuels	Energy from coal (cement pyroprocessing)	2.60E-02	1.63E-02	1.18E-02	0.00E+00

Table 8 Weighted value of impact category for all concrete mixes

Impact category	**Impact Indicator**	**Air Component**	**CON OPC**	**CON PPC**	**CON PSC**	**CON GP**
Human Health	Respiratory inorganics	CO	1.52E+00	1.11E+00	8.01E-01	2.22E-03
		NOx	2.46E+00	1.86E+00	1.46E+00	7.02E-01
		SO_2	9.55E-01	7.26E-01	5.96E-01	2.35E-01
		dust (PM 10)	9.29E-01	8.06E-01	7.26E-01	7.40E-01
	Respiratory organics	VOC	1.75E-04	1.38E-04	1.00E-04	2.50E-05
Total			**5.87E+00**	**1.50E-02**	**4.50E+00**	**1.19E-02**
Ecosystem quality	Ecotoxicity	Lead	3.74E-10	2.81E-10	2.11E-10	0.00E+00
	Acidification/ Eutrophication	NOx	6.40E-06	4.85E-06	3.80E-06	1.82E-06
		SO_2	5.64E-06	4.29E-06	3.52E-06	1.38E-06
Total			**1.20E-05**	**9.13E-06**	**7.32E-06**	**3.21E-06**
Resources	Fossil fuels	Energy from coal (cement pyroprocessing)	5.19E+00	3.27E+00	2.36E+00	0.00E+00
Single score value			**11.06**	**7.77**	**5.95**	**1.68**

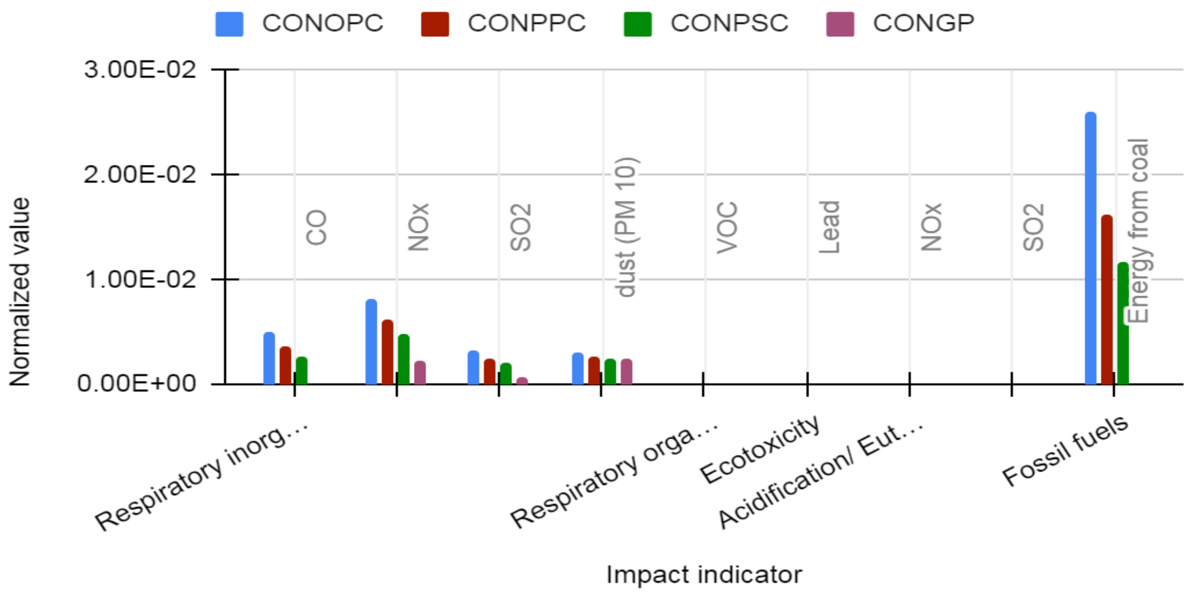

Fig. 8 Normalized value of impact indicators with respect to air pollutants

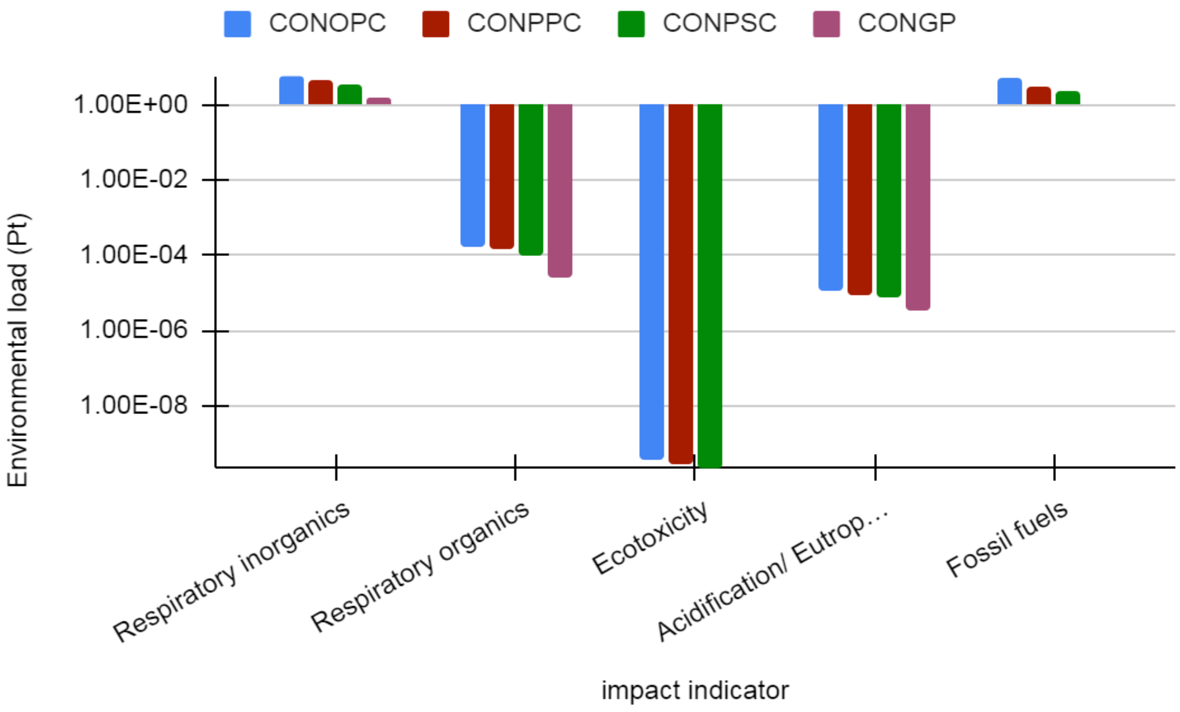

Fig.9 Weighted value of impact indicators

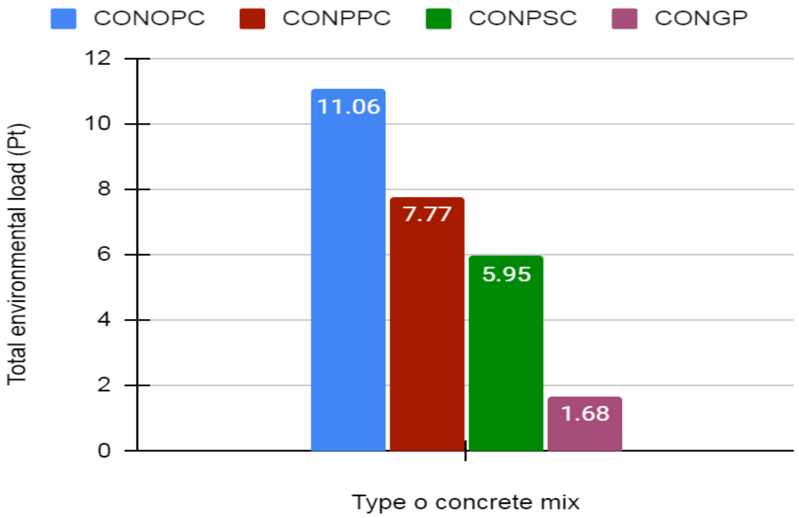

Fig.10 Single score value of all impact categories

5.0 Conclusion, Limitations and Future scope

In today's time when every part of the world is experiencing the consequences of global warming and subsequent climate changes in terms of heavy rain and elevated temperatures, it has become essential for everyone to contribute their part to reduce emissions responsible for the same and choose materials and processes wisely. The study demonstrated that replacing cement with other materials such as FA and GGBS that are byproducts of industrial processes can produce more sustainable concrete. It is clear that CONGP is the most promising concrete in terms of sustainability. Both CONPPC and CONPSC performed better than ordinary concrete mixed with Portland cement. In addition, PSC would provide further benefits than PPC in terms of environmental sustainability because a higher percentage of cement clinkers can be replaced by PSC than PPC. Life cycle cost analysis can be done further to get an exact idea of the overall cost of all four mixes. The present study includes the evaluation of environmental impacts of four mixes from raw material extraction to production, i.e., a cradle-to-gate approach is adopted. It does not include further transportation, usage, and disposal of the concrete. The present work can be extended further to identify the environmental impact of the four mixes from cradle to grave. Also, emission to water and land could be explored to get more detailed results of impact indicators.

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