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Life Cycle Impact Assessment of Recycled Aggregate Concrete, Geopolymer Concrete, and Recycled Aggregate-Based Geopolymer Concrete

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Abstract: This study presents a life cycle impact assessment of OPC concrete, recycled aggregate concrete, geopolymer concrete, and recycled aggregate-based geopolymer concrete by using the mid-point approach of the CML 2001 impact-assessment method. The life cycle impact assessment was carried out using OpenLCA software with nine different impact categories, such as global warming potential, acidification potential, eutrophication potential, ozone depletion potential, photochemical oxidant formation, human toxicity, marine aquatic ecotoxicity, and freshwater and terrestrial aquatic ecotoxicity potential. Subsequently, a contribution analysis was conducted for all nine impact categories. The analysis showed that using geopolymer concrete in place of OPC concrete can reduce global warming potential by up to 53.7%. Further, the use of geopolymer concrete represents the reduction of acidification potential and photochemical oxidant formation in the impact categories, along with climate change. However, the potential impacts of marine aquatic ecotoxicity, freshwater aquatic ecotoxicity, human toxicity, eutrophication potential, ozone depletion potential, and terrestrial aquatic ecotoxicity potential were increased using geopolymer concrete. The increase in these impacts was due to the presence of alkaline activators such as sodium hydroxide and sodium silicate. The use of recycled aggregates in both OPC concrete and geopolymer concrete reduces all the environmental impacts.

Keywords: life cycle; impact assessment; recycled material; geopolymer concrete; sustainability

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1. Introduction

Concrete is the most widely used construction material and the second most-consumed substance on earth, after water [1]. Ordinary portland cement (OPC) used in concrete production has detrimental effects on the environment due to the release of a high amount of greenhouse gas, especially CO_2. One ton of CO_2 is released by the production of one ton of OPC [1,2]. According to research conducted in Hawaii in the year 2020, it was reported that the amount of CO_2 in the atmosphere reached the highest level of 417.1 ppm [3]. Moreover, there exist other environmental issues, such as the dumping of construction and demolition wastes. Hence, it is crucial to develop environmentally sustainable solutions in the construction industry.

Researchers developed the idea of introducing alternative binders to OPC that not only reduce CO_2 production but also resolve the disposal problems. One such alternative is a geopolymer concrete (GPC) technology that promotes sustainable development. Its efficient performance depends on both the composition of the source material and the activator used [4]. Moreover, the use of recycled aggregates (RA) in GPC provides both eco-friendly and economical solutions by addressing the issue of dumping demolition wastes.

Peem et al. [5] investigated the influence of RA on high-calcium fly ash (FA)-based GPC at different molarities. It was found that the RA can be used in FA-based GPC with an early age strength of about 30.6–38.4 MPa, slightly lower than normal aggregate FA-based GPC. Likewise, Xie et al. [6] studied the combined effect of FA and ground granulated blast-furnace slag (GGBFS) on recycled aggregate geopolymer concrete (RAGC), and reported that RAGC with a 50% FA and 50% GGBFS binder content exhibits a superior synergetic effect on mechanical and workability properties. Further, it was found that the use of metakaolin fly ash (MK-FA)-based binders in RAGC resulted in better mechanical and durability properties [7]. Hence, the use of MK-FA-based GPC with 100% recyclable coarse aggregates provides an environmentally sustainable solution. While assessing the environmentally sustainable performance of GPC compared to OPC concrete, there are a lot of techniques and procedures used. One such assessment technique used is the life cycle assessment (LCA).

LCA is a 'cradle-to-grave' or 'cradle-to-gate' assessment technique used to evaluate the environmental impacts from raw material extraction to the demolition application stage [8,9]. This tool plays an important role in the environmental management of a given product system that further involves an environmental comparison of different prototypes. It is a policy or program applied in GPC technology to justify that GPC has less potential to degrade the environment, compared to OPC concrete.

Different studies have been conducted to assess the global warming potential (GWP) and environmental impact assessment of GPC [4,8–13]. Daniel et al. [9] analyzed the life cycle inventory of GPC and OPC concrete from lab to industrial scales, based on the source of a sodium hydroxide (NaOH) activator. It was found that GPC exhibits 64% less GWP than OPC concrete if the source of NaOH is local solar salt. Rishabh et al. [10] investigated the environmental impact assessment of SF-FA-based GPC activated with both NaOH and sodium silicate (Na_2SiO_3) separately. It was concluded that OPC has a greater GWP than GPC, and further, that SF-FA-based GPC activated with NaOH has a lesser environmental potential when compared to GPC activated with Na_2SiO_3.

Many researchers have investigated the LCA of GPC [7,9–11,14,15], but as per the authors' knowledge, no systematic and detailed study has been devised to study the LCA of RAGC along with its comparison with mixtures of GPC, RAC, and OPC concrete. For example, how does RA impact the LCA of GPC and OPC concrete? What is the GWP of RAGC? How do RAGC and other mixtures impact the other environmental factors, such as GWP, acidification potential (ADP), photochemical oxidants formation (POF), and ozone depletion? These opacities still need to be answered. Hence, endorsing that idea, this study intends to investigate the environmental impact assessment of RAGC using the LCA approach.

2. Materials and Methods

The LCA methodology for all four mixes is performed in four steps, as per ISO 14040 and 14044 [16]. The first step is to define the goal and scope of the research, while the second and third steps are to conduct inventory analyses and life cycle impact assessments (LCIA), respectively. The last step is to conduct an interpretation based on inventory and impact-assessment analysis. Lastly, the methodology adopted to conduct the life cycle inventory is presented in the form of a flow chart.

2.1. Goal and Scope

In the present research, the goal of the LCA is to find out the impact of the inclusion of RA in both concrete and GPC on the environment, and to compare the environmental impacts of four mixes, i.e., the OPC concrete, RAC, GPC, and RAGC. The scope of the LCA begins with the extraction of the natural resources, including aggregates, the raw material for cement, and alkali activators, and ends with the GPC production with processed RA. The raw material from natural reserves is utilized in producing OPC concrete, which, after demolition, can be utilized as RA for the GPC mix.

For the RAGC mix, the FA was considered as an aluminosilicate source while sodium hydroxide and sodium silicate were used as an activator. The production of silicates and hydroxide from the raw material to the end product was considered in conducting the life cycle inventory analysis. After defining the goal and scope, the functional unit was set as 1 m^3 of GPC, RAGC, and RAC of a specific strength and compared with OPC concrete. The strength conditions considered in this research study varied from 25–30 MPa for all four types of mixtures. However, the system boundaries specified in this research study started from the collection of their ingredients to their production, as presented in Figure 1.

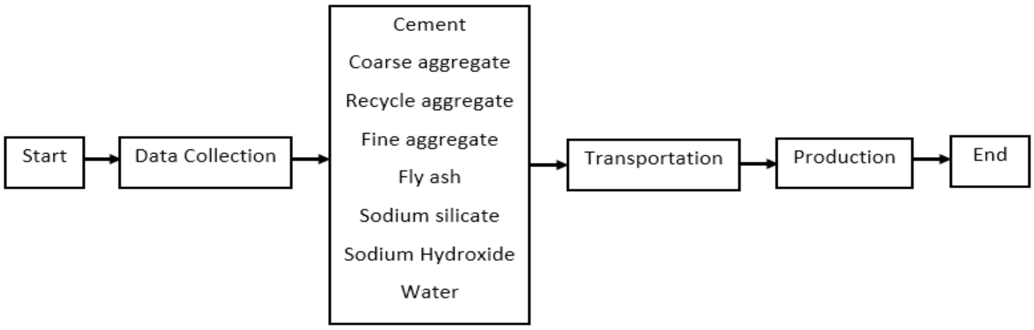

Figure 1. System boundaries of concrete.

Further, the mix design data of RAC, GPC, RAGC, and OPC concrete were taken from the literature [16,17]. Further, the emissions data of the respective activities in the production of all concrete mixtures were taken on the basis of the geography of Pakistan. However, the missing data were taken from the ecoinvent database source [18]. In addition, it was assumed that the production and transportation conditions of all concrete mixtures are the same as that of the conditions that exist in the respective locations from where the emissions data were collected. The output emissions depend only on the consumption of energy in the production processes of all the concrete mixtures.

2.2. Study Area

The LCA methodology for four different concrete mixtures was applied based on the inventory analysis applied in the city of Abbottabad, Pakistan. The location of COMSATS University Islamabad, Abbottabad Campus (CUI, atd), was assumed as the production location for all the four mixtures. Furthermore, the collection of cement, coarse aggregate, and fine aggregate were considered at the location of the Bestway Cement factory in Haripur, the Choona Crushing plant in Abbottabad, and Thore in Muzaffarabad, respectively.

2.3. Mix Design adaptation

The mix design of normal concrete and the RAC mixture was taken from the study conducted in Pakistan [16]. The natural aggregate was fully replaced (i.e., 100% replacement) with RA in this study. Both types of concrete have 28 days' compressive strengths of 28 MPa. However, the mix design procedure for the GPC and RAGC mixtures was taken from [17], with the compressive strength of 30 MPa and 27 MPa, respectively. A total of 40% of the normal coarse aggregate was replaced with RA in the RAGC mixture. The mix design for all four mixtures is presented in Table 1.

Table 1. Mix design of four concrete mixtures.

Ingredients	OPC Concrete (kg/m^3) [16]	RAC (kg/m^3) [16]	GPC (kg/m^3) [17]	RAGC (kg/m^3) [17]
Cement	415	415	-	-
Fly ash	-	-	408	408
Fine aggregate	620	620	554	554
Coarse aggregate	1040	-	1243	746
Recycled aggregate	-	1040	-	497
Water	185	185	20	20
Sodium Hydroxide	-	-	41	41
Sodium Silicate	-	-	103	103
Superplasticizer SP (% of cement)	0.5	1.5	-	-

2.4. Inventory Analysis

The life cycle inventory is the next step, after defining the goal and scope. Mostly, the data of concrete production were based on a questionnaire survey of local producers and suppliers in the city of Abbottabad, Pakistan. However, missing data were taken from the literature and the ecoinvent database, version 3.7.1. The cutoff classification method was considered the system model in the ecoinvent database [18]. The cutoff approach was based on the assumption that the primary producer of any material is allocated to a primary consumer and has no impact or credit on its recycled material.

In the present research, the data of emissions of different production processes for the geography of Pakistan are generated on the basis of an emission/energy ratio method. The inventory data of emissions and energy for all the ingredients of OPC concrete and GPC are taken from the literature [18–21]. In the next step, the ratio of emission/energy (kg/MJ) is calculated for each ingredient in the respective technical paper. After taking the average of the emission/energy ratio of each ingredient, it was then multiplied by the energy produced (in MJ) by every ingredient, with respect to the location in Pakistan. Moreover, the flow of taking inventory data was presented in the form of a flow chart (Figure 2).

2.5. Questionnaire Survey

The data for calculating the total energy produced by each ingredient, i.e., fine aggregate, coarse aggregate, RA, and cement, are based on the questionnaire survey in the region of Abbottabad city. The data for the cement are taken from the Bestway Cement industry in the Hattar Industrial Estate, KPK. Further, the data for the coarse aggregate are taken from the Choona crushing plant in Abbottabad (Figure 3). The fine aggregate is taken from the Neelum riverbed at the Thore Site in Muzaffarabad (Figure 4). The energy data of the sand are based on the excavator method, adopted at the location of Thore, Muzaffarabad, using a medium-load truck for transportation to the final location. Moreover, the total energy considered is the summation of both manufacturing energy and transportation energy, with respect to the selected reference point.

For determining the transportation energy of the cement and the aggregates, the material suppliers near COMSAT University Islamabad, Abbottabad Campus, were assumed to be the final location where the all ingredients of concrete are supplied. The calculation of transportation distances relied on the Google Maps application. In addition, the transportation of cement, coarse aggregate, and RA to the destination used the heavily loaded truck. In case of RA, the site near Dhamtor, Abbottabad was considered as the dumping site for construction and demolition waste. For the RAC, the natural raw material and mining activity for aggregate production was set to zero. Similarly, the raw material was taken as zero for FA aluminosilicate, as it is a by-product of the coal industry. The cutoff allocation procedure was assumed, which showed that FA is a by-product and has no impact on life cycle inventory emissions. However, the raw materials inventory for the silicate production was taken from the literature. Additionally, the inventory for sodium hydroxide production was based on the ecoinvent database. The life cycle inventory, based on the questionnaire survey, is presented in Table 2.

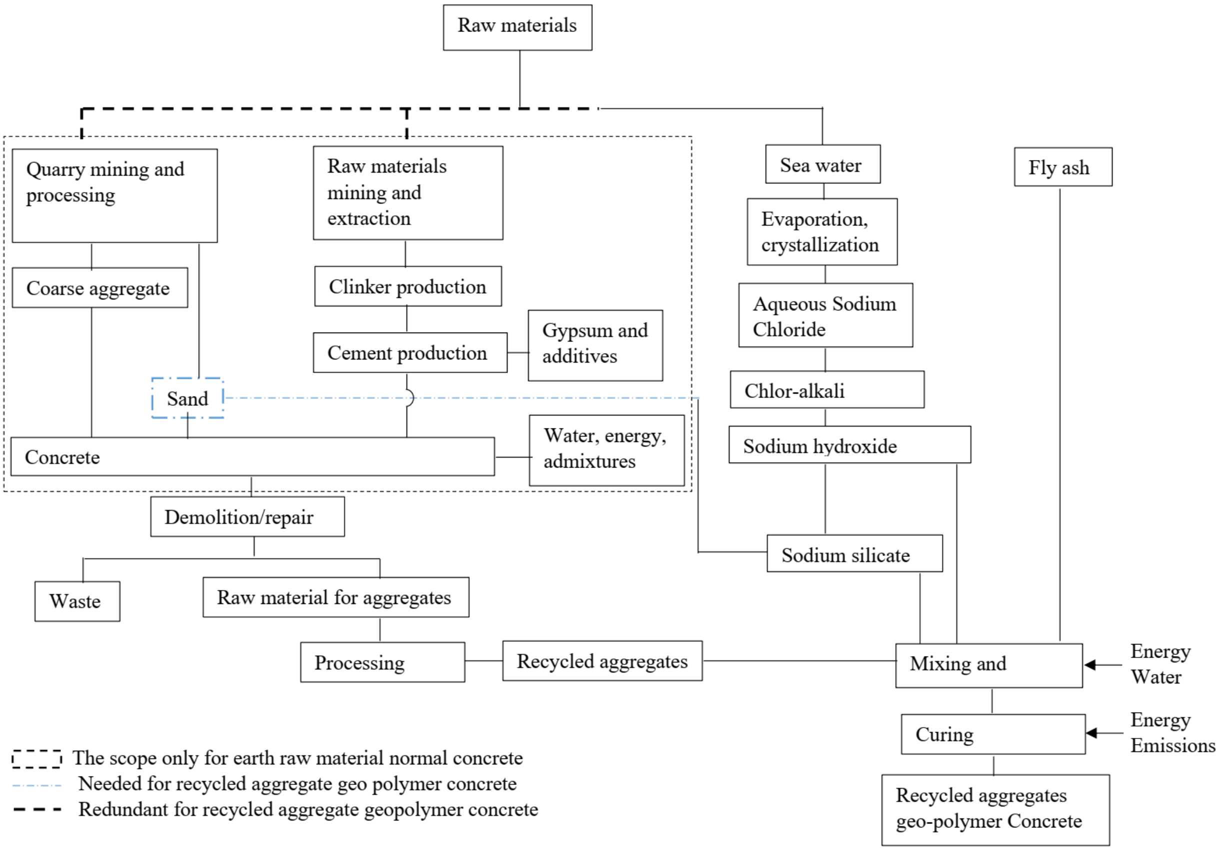

Figure 2. Life cycle inventory flow of OPC concrete and RAGC.

Figure 3. Mining and Crushing at the Choona Site, Abbottabad.

Figure 4. Sand Extraction near the Neelam Riverbed, Muzaffarabad.

Table 2. Life Cycle Inventory for ingredient of concrete.

Ingredient	Cement	Coarse Aggregate	Fine Aggregate	Recycled Aggregate
Total Energy (MJ/kg)	2.973	0.0154	0.0136	0.00833
Emissions (kg)				
CO_2	0.614	0.00173	0.00095	0.00124
SO_2	0.0014	6.976×10^{-6}	1.99×10^{-6}	2.091×10^{-6}
CO	0.0026	0.001437	3.46×10^{-6}	2.394×10^{-6}
NO_x	0.00141	1.128×10^{-5}	7.25×10^{-6}	8.202×10^{-6}
PM < 10	0.000267	1.281×10^{-5}	1.1×10^{-5}	7.097×10^{-6}
NMVOC	0.000161	6.455×10^{-7}	6.4×10^{-10}	4.320×10^{-7}
NH_3	1.893×10^{-5}	-	3.37×10^{-9}	-
N_2O	1.357×10^{-6}	2.813×10^{-8}	3.29×10^{-7}	1.535×10^{-8}
CH_4	0.000655	6.979×10^{-7}	1.88×10^{-8}	3.629×10^{-7}

2.6. Life Cycle Impact Assessment (LCIA)

The impact was analyzed by using OpenLCA software with a mid-point approach, called CML 2001 baseline (Centrum voor Milieukunde Leiden). There were a number of impact categories that were analyzed by the CML approach for the ecoinvent dataset. However, in the present research work, nine impact categories were analyzed, i.e., GWP, ADP, photochemical oxidants formation (POF), ozone depletion, human toxicity, marine aquatic ecotoxicity, freshwater aquatic ecotoxicity, and eutrophication potential. The above-mentioned impact categories were analyzed and compared to four types of mixes, i.e., concrete mix, RAC, GPC, and RAGC. The category indicators can be expressed in the form of equations, as presented below:

$$\text{GWP} = \sum \text{Load (i)} \times \text{GWP (i)}$$

$$ODP = \sum Load\ (i) \times ODP\ (i)$$
$$ADP = \sum Load\ (i) \times ADP\ (i)$$
$$POF = \sum Load\ (i) \times POF\ (i)$$
$$HTP = \sum Load\ (i) \times HTP\ (i)$$
$$EP = \sum Load\ (i) \times EP\ (i)$$

where,
Load (i) is the environmental load of the respective inventory item (i);
GWP (i), ODP (i), ADP (i), POF (i), HTP (i), and EP (i) are the characterization factors for the GWP, ODP, ADP, POF, HTP, and EP inventory items (i), respectively.

3. Results and Discussion

In this section, the environmental impacts and process contributions of four different concrete mixtures are analyzed and compared using a mid-point approach, called CML 2001. In the first section, the life cycle inventory results for the ingredients of concrete are reported. In the next section, the numbers of impact categories are analyzed for four types of mixes, i.e., concrete mix, RAC, GPC, and RAGC. At last, the contribution analyses of all four concrete mixtures are presented.

3.1. Life Cycle Inventory Results

Based on the questionnaire survey and the emission/energy procedure, it was concluded that the total energy (the sum of electric, coal, and transportation energy) required for one kilogram of cement is 2.973 MJ/kg. However, the total energy required for the coarse aggregate (the sum of mining, crushing, and transportation energy) and RA (the sum of crushing and transportation energy) are 0.0154 MJ/kg and 0.00834 MJ/kg, respectively. The total energy required for sand production and transportation is 0.0136 MJ/kg. The energy data for all ingredients, along with the transportation energy, are given in Table 3.

Table 3. Energy production by all ingredients through questionnaire survey.

Ingredients	Production Energy (MJ/kg)	Transportation Energy (MJ/kg)
Cement	2.918	0.055
Fine Aggregate	0.00565	0.00795
Coarse Aggregate	0.00873	0.00630
Recycled Aggregate	0.00524	0.00309

3.2. Environmental Impact Analysis of Four Mixes

In this study, the environmental impacts were analyzed for the comparison of normal concrete and GPC along with their RAC. From the Open LCA software, the impacts were analyzed that represented that the inclusion of an alternative binder or RA could help to reduce the certain environmental impacts were analyzed. The most concerning impact category in the construction industry is the GWP that results from CO_2 production and the emissions of GHGs [14]. The GWP-100a (100-year global warming potential) of OPC concrete, RAC, GPC, and RAGC are compared and presented in Figure 5. It is shown that OPC concrete has the highest GWP when compared to the other three mixes. The GWP follows a decreasing pattern from normal concrete, > RAC > GPC > RAGC, as shown in the respective figure. This pattern provides the idea that the mixes containing higher contents of cement have higher GWPs, when compared to the others. However, with the inclusion of RA in the mix, the net impact of global warming is reduced [17,22–26].

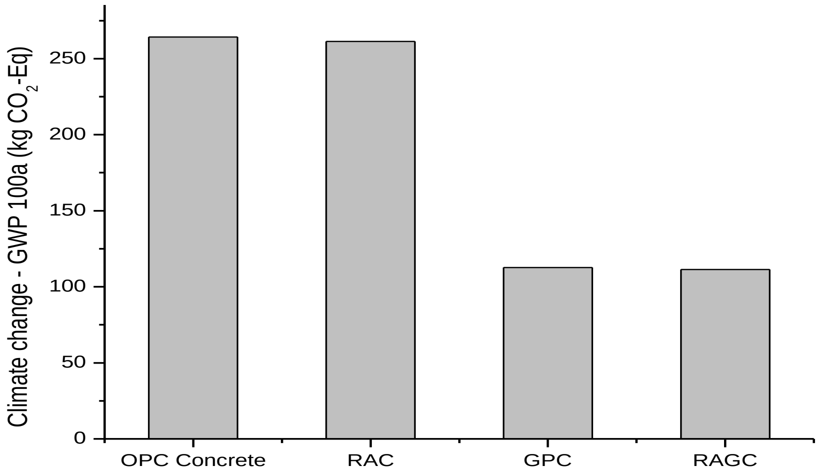

Figure 5. Climate change GWP of four mixes.

In addition, ADP follows the same pattern as GWP for the four types of concrete mixtures. The normal concrete has the highest impact on acidification due to high emissions of air pollutants, such as NOx, SO_2, NH_3, etc., during cement production. From Figure 6, it is concluded that RAC and RAGC exhibit lower ADP when compared to normal concrete and GPC, respectively, due to the recycling of coarse aggregates. The recycling of coarse aggregates requires lower energy than the normal aggregate, due to the elimination of mining energy and the reduction in transportation energy. It is reported that the net environmental impacts of RAC are also influenced by the transportation distance [20,21,27,28]. The environmental impact of RAC has a lower influence if the transportation distance is less than 20 km for the considered natural aggregate when it is compared [26,27].

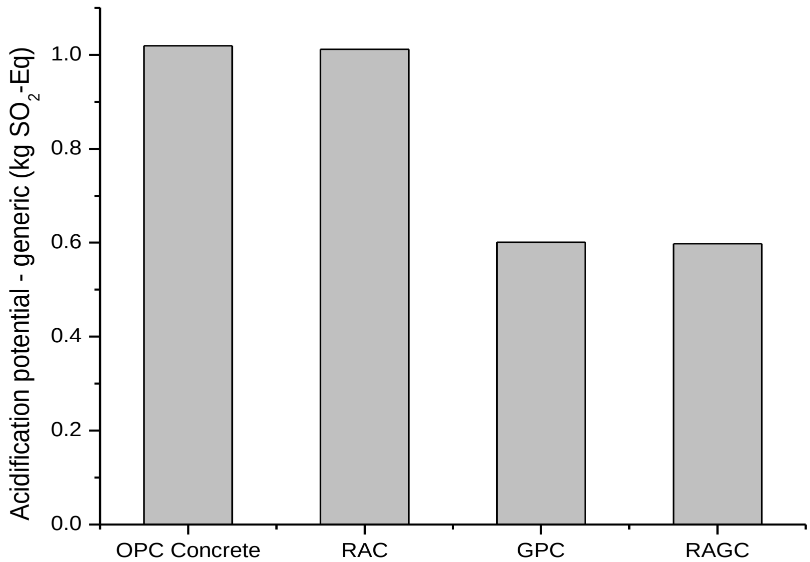

Figure 6. Acidification potential for four mixes.

Additionally, the ozone depletion potential of the four types of mixes is presented in Figure 7, which clearly shows that the production of concrete and RAC mixtures has no direct impact on ozone depletion for a specified functional unit of 1 m^3 of concrete samples. Conversely, both type of geopolymer mixes, i.e., GPC and RAGC, have a significant impact on ozone depletion. This impact is due to the presence of a sodium hydroxide activator in FA-based GPC mixtures. The production of sodium hydroxide through the process of chlor-alkali electrolysis, using a membrane cell, emits some amount of tetra-chloro methane in the atmosphere, which could impact the ozone layer.

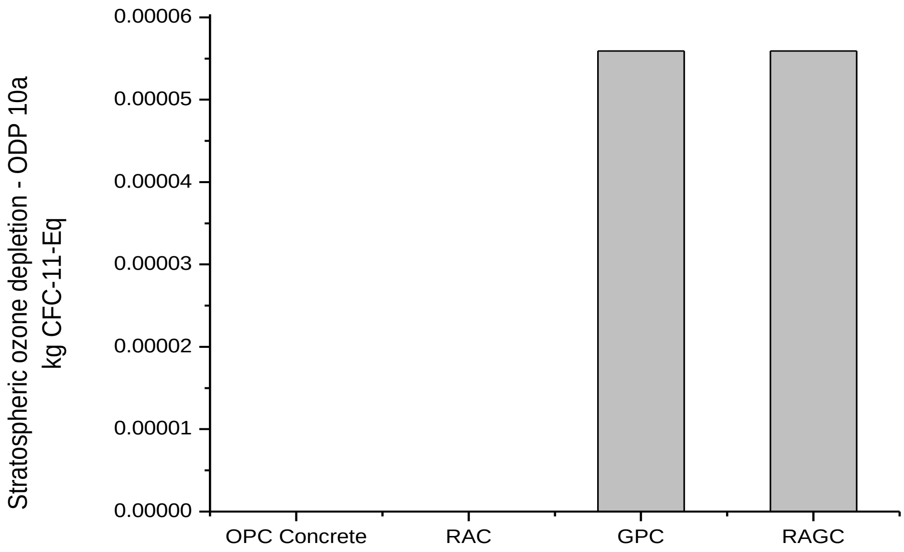

Figure 7. Ozone depletion potential of four mixes.

The impact of different environmental pollutants on air pollution, specifically ozone depletion, is a very complex process. The characteristics of environmental pollutants depend on their nature—whether either is a primary or secondary pollutant. The direct emissions of gases, fumes, and smoke from the exhausts of vehicles and combustion factories, along with the burning of fossil fuels, are the causes of the primary pollutants. The primary pollutants, such as particulates, hydrocarbon, nitrogen oxides, and carbon monoxide, etc., when coming in contact with other pollutants such as VOC or compounds of ammonia (coming from other developmental activities), form the secondary pollutants. Their chemical reactions in the atmosphere increase the impact on urban air quality by acid deposition and the formation of ground-level ozone (bad ozone or tropospheric ozone). However, the presence of chemicals, such as manufactured halocarbon refrigerants, propellants, solvents, and foam-blowing agents (CFCs, HCFCs, and halons), promotes the depletion of the ozone hole (beneficial ozone or stratospheric ozone). The emissions resulting from the production of concrete influence the presence of photochemical oxidants that affect the tropospheric ozone.

However, the photochemical oxidation of four concrete mixes is represented in Figure 8, which shows that the concrete mixture has the highest ability to produce photochemical oxidants in the atmosphere. These oxidants are produced from the reaction of primary air pollutants such as NO_x, SO_x, and hydrocarbons under the action of sunlight [29]. The decreasing pattern of this impact category starts from concrete to the RAGC mixture, i.e., normal concrete > GPC > RAGC > RAC. The production of elementary environmental pollutants during cement production and transportation is responsible for the highest photochemical oxidation when compared to the other mixtures. The production of photochemical oxidants adversely influences the atmosphere by the incorporation of unwanted ozone molecules in the troposphere and, thus, causes smog, along with other environmental effects.

The impact category, namely, the ETP of the four concrete mixtures, is shown in Figure 9, which concludes that GPC has the highest ETP (0.1148 kg PO_4-Eq/m^3 of GPC) when compared to the other mixtures. This is due to the presence of hydroxide and silicate sources in GPC [15]. On the other hand, the RAC and RAGC represent a slight decrease of impact categories, when compared to OPC concrete and GPC, respectively. The use of RA is responsible for less NO_x, SO_2, and ammonia emissions, when compared to normal aggregate production.

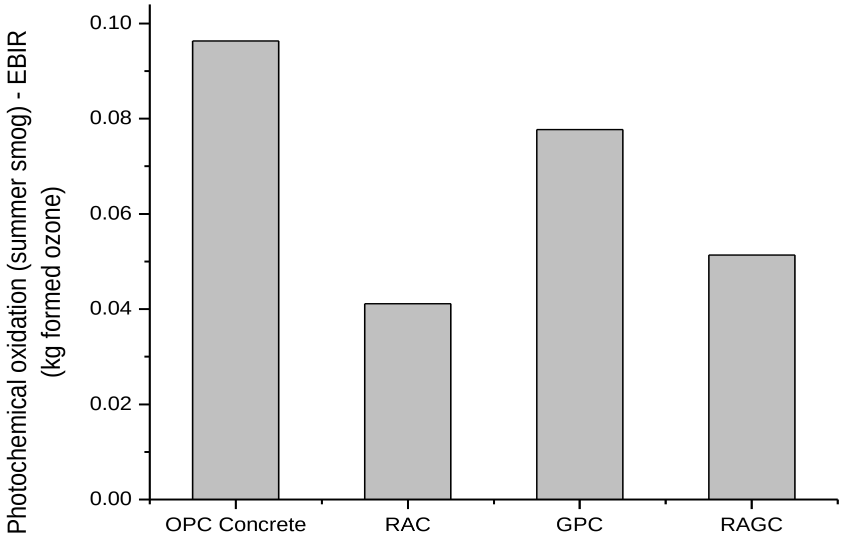

Figure 8. Photochemical oxidation of four mixes.

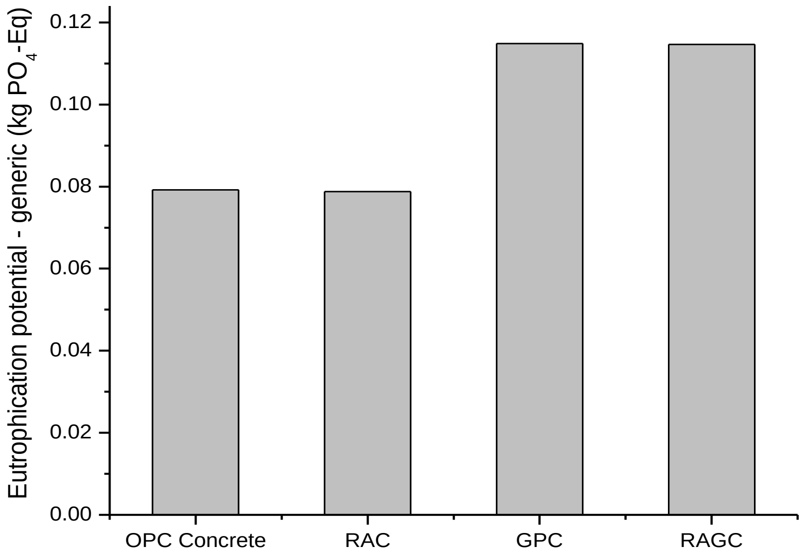

Figure 9. Eutrophication potential of four mixes.

However, HTP describes the potential damage of the chemical unit that is released in the atmosphere. Its potentiality depends on both the inherent toxicity of the chemical and its potential dose. From Figure 10, it is represented that GPC has a higher impact on human toxicity when compared to the other three mixes. The pattern of HTP for all four mixtures represents that the GPC binder with natural or RA shows a higher potency due to presence of alkaline activators, especially a sodium silicate source [10,12,30]. Similarly, the impact category, called marine aquatic ecotoxicity potential (MAETP), is shown in Figure 11. The MAETP of OPC concrete, RAC, GPC, and RAGC are 4.57×10^{-5}, 4.47×10^{-5}, 136.45, and 136.45 kg of 1.4 DCB-Eq/m^3 of mixture, respectively. The values predict that the OPC and RAC concrete has minute impact on aquatic ecotoxicity due to the absence of an alkaline activator, as in the case of the geopolymer mixtures. The aquatic ecotoxicity can be hindered by using sustainable production sources of alkaline activators.

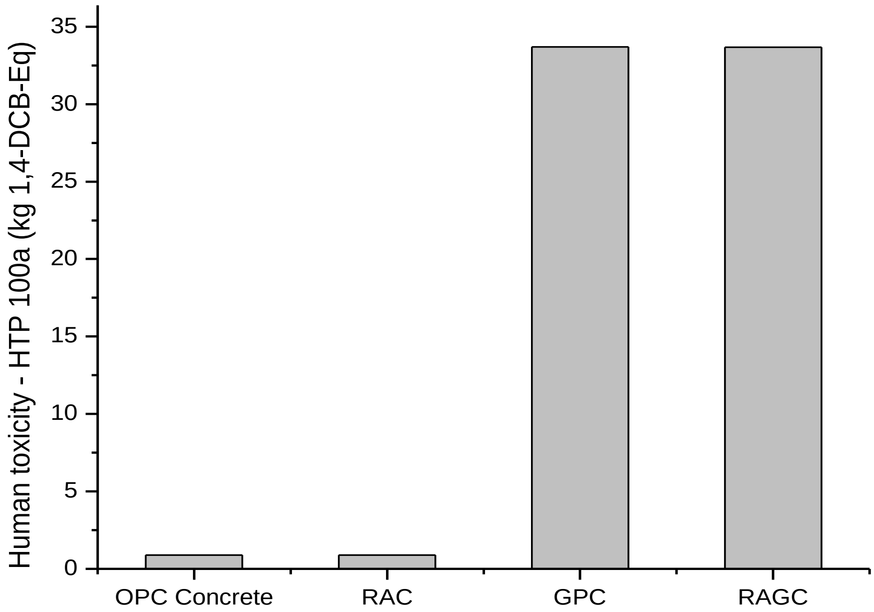

Figure 10. HTP of OPC concrete, RAC, GPC, and RAGC.

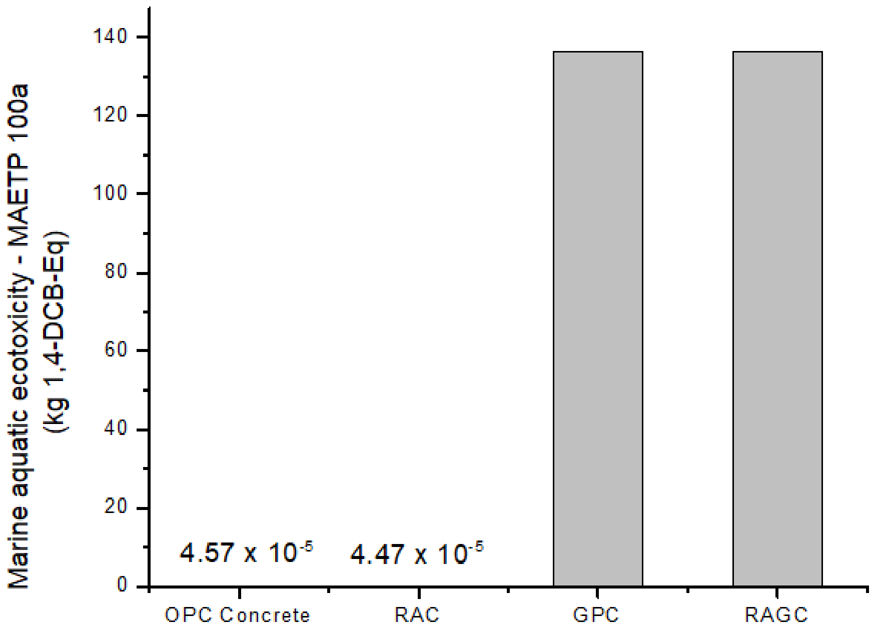

Figure 11. MAETP of OPC concrete, RAC, GPC, and RAGC.

The last two impact categories considered in this research study are freshwater aquatic ecotoxicity potential (FAETP) and terrestrial aquatic ecotoxicity potential (TAETP), as shown in Figures 12 and 13, respectively. From Figure 12, it is clearly seen that the GPC mixture has a higher FAETP value when compared to the other mixtures. The decreasing pattern of both impact categories, i.e., GPC > RAGC > OPC concrete > RAC, depicts that the presence of a silicate and hydroxide source in GPC mixtures is responsible for a higher ecotoxicity impact [10,13,30]. However, the terrestrial aquatic ecotoxicity of both GPC mixtures shows the same value of 0.0107 kg 1,4 DCB-Eq, as presented in Figure 13. This depicts that the impact category is only affected by the presence of a sodium silicate and sodium hydroxide source in both mixtures.

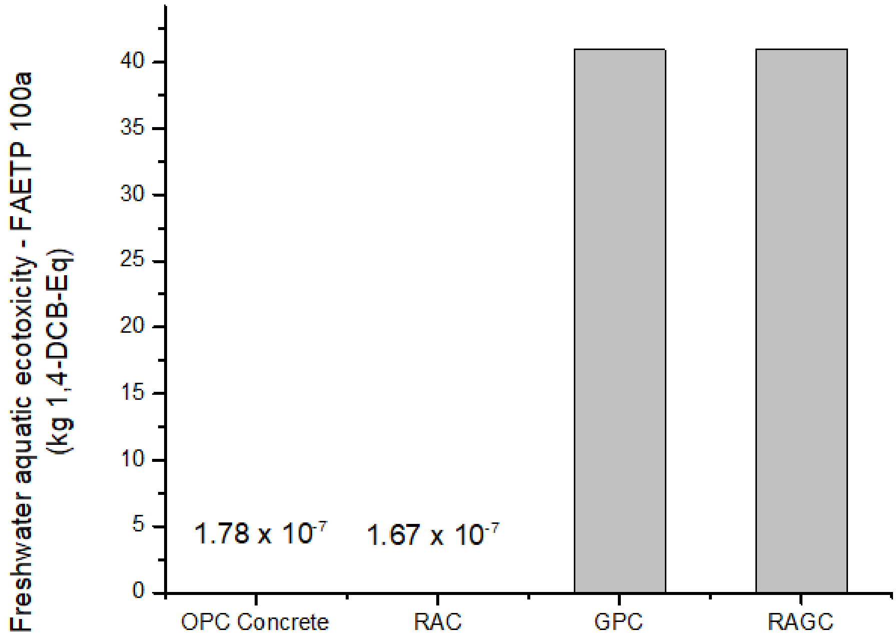

Figure 12. FAETP of OPC concrete, RAC, GPC, and RAGC.

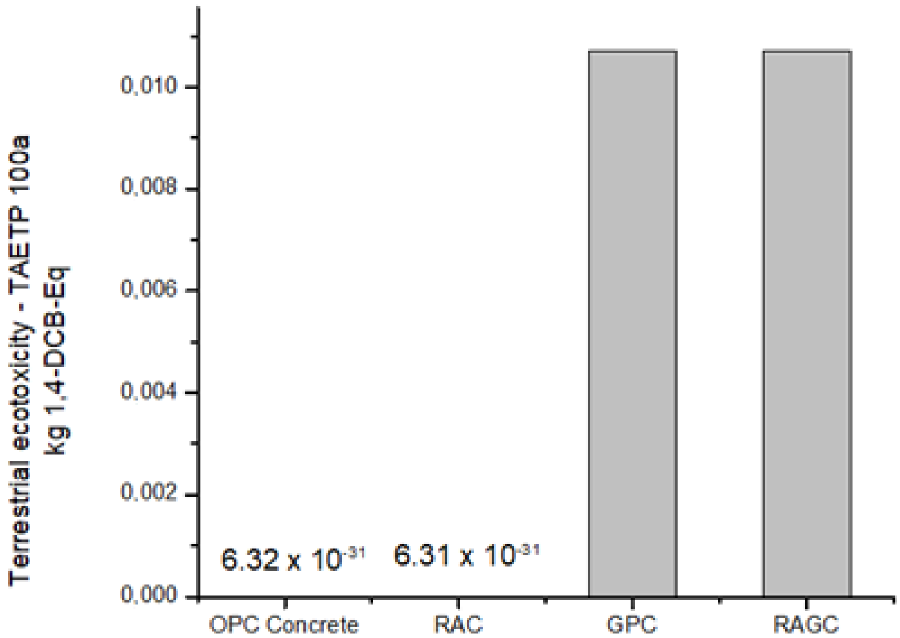

Figure 13. TAETP of OPC concrete, RAC, GPC, and RAGC.

In the present impact assessment analysis, it is concluded that the OPC concrete has potentially higher impacts than GPC and recycled mixtures in the impact categories GWP, ADP, ETP, and POF. The use of GPC can reduce GWP significantly—up to 57.34%—when compared to normal concrete. However, other impact categories, such as FAETP, MAETP, stratospheric ozone depletion, HTP, and TAETP, show a greater impact of GPC than normal concrete. This is due to the presence of alkaline activators, such as a silicate source, in the GPC [10,12,30]. Moreover, the recycling of coarse aggregates in both concrete and GPC mixtures can reduce the overall environmental impacts. The values of the potential impact categories of the four mixtures by the CML baseline method are presented in Table 4.

Table 4. Impact categories by CML baseline method.

Indicator	OPC Concrete	RAC	GPC	RAGC	Units
Acidification Potential—Generic	1.01904	1.01165	0.60119	0.59769	kg SO_2-Eq
Climate Change—GWP	264.181	261.315	112.743	111.377	kg CO_2-Eq
Eutrophication Potential	0.07922	0.0788	0.11483	0.11463	kg PO_4-Eq
Freshwater Ecotoxicity	1.78×10^{-7}	1.677×10^{-7}	40.940	40.940	kg 1,4-DCB-Eq
Human toxicity	0.8952	0.8860	33.70	33.68249	kg 1,4-DCB-Eq
Marine aquatic Ecotoxicity	4.575×10^{-5}	4.475×10^{-5}	136.45	136.45	kg 1,4-DCB-Eq
Photochemical Oxidation	0.0963	0.0411	0.0777	0.0513	kg ozone formed
Stratospheric ozone depletion	0	0	5.59×10^{-5}	5.59×10^{-5}	kg CFC-11-Eq
Terrestrial Ecotoxicity	6.32×10^{-31}	6.30×10^{-31}	0.0107	0.0107	kg 1,4-DCB-Eq

However, the nine considered environmental indicators in this research work were scaled while keeping the potential environmental damage to the surrounding atmosphere in view. The GWP is ranked highest, followed by ODP, POF, HTP, ADP, EP, FAETP, MAETP, and TAETP. From the weighted average of all the indicators from all the mixtures, it is concluded that the RAGC mixture is more sustainable for the environment, followed by GPC, RAC, and OPC concrete mixtures. The ranking of all the mixtures regarding their environmentally sustainable performance is given in Table 5. This ranking will provide an idea to civil society about which concrete mixture efficiently provides for structural needs and offers sustainable solutions to the environment. Depending on the strength requirement, the audience can select the required aluminosilicate and activator source along with the choice of selection of recycled aggregate or natural aggregate. In the present research work, the RAGC is the best-optimized mixture for meeting the structural needs and for hastening sustainable developments.

Table 5. Ranking of mixtures on the basis of environmentally sustainable performance.

Ranking	Mixture
1st	RAGC
2nd	GPC
3rd	RAC
4th	OPC

3.3. Contribution Analysis

A contribution analysis for the four selected mixtures was performed to check the contribution of the selected processes to the chosen LCIA impact category. The contribution of coarse aggregate, fine aggregate, cement, and the mixing process was checked in the analysis of OPC concrete, while the contribution of RA, fine aggregate, cement, and the mixing process was checked in the RAC analysis. Figures 14 and 15 show that the cement had the highest negative impacts on the chosen environmental categories [10,11,31]. In the case of OPC concrete, cement had the highest impact, followed by coarse aggregate and fine aggregate. The categories GWP, ADP, HTP, and EP are mostly affected by cement because of higher CO_2, SO_x, and NO_x emissions created during its manufacturing and transportation. However, coarse aggregate and cement contribute 57.4% and 41.5% to the POF, respectively. This is due to the presence of both mining and crushing activities that lead to more emissions of particulate matter (PM), volatile organic compounds, SO_2, and NO_x [10].

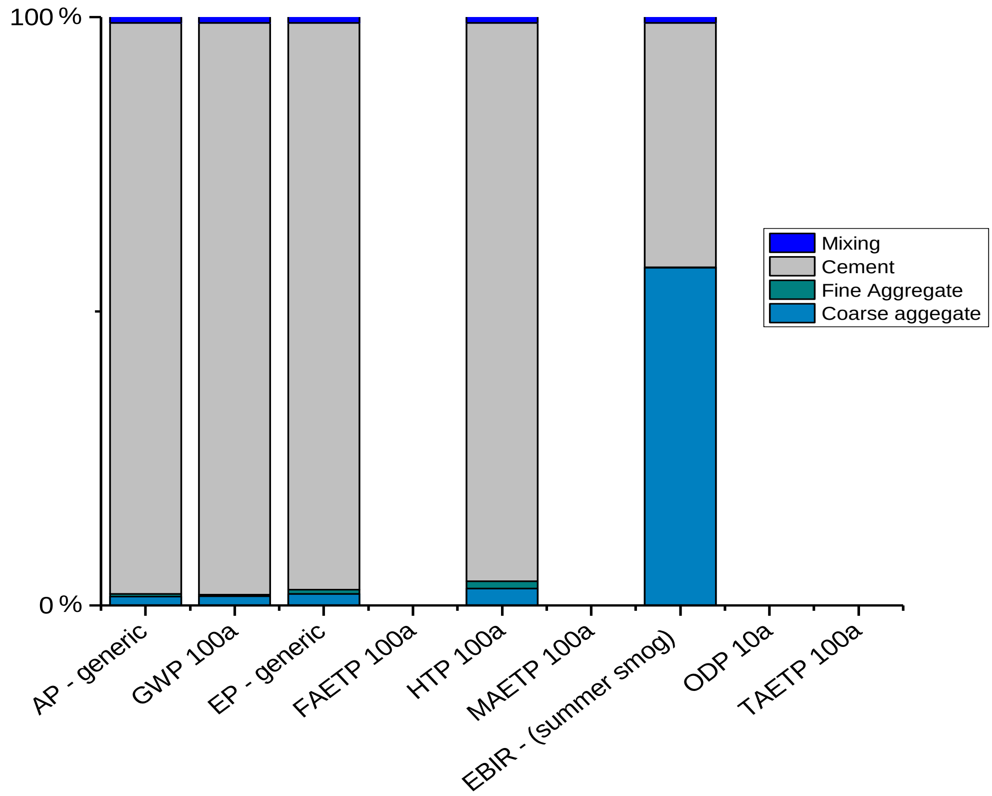

Figure 14. Contribution Analysis for OPC concrete.

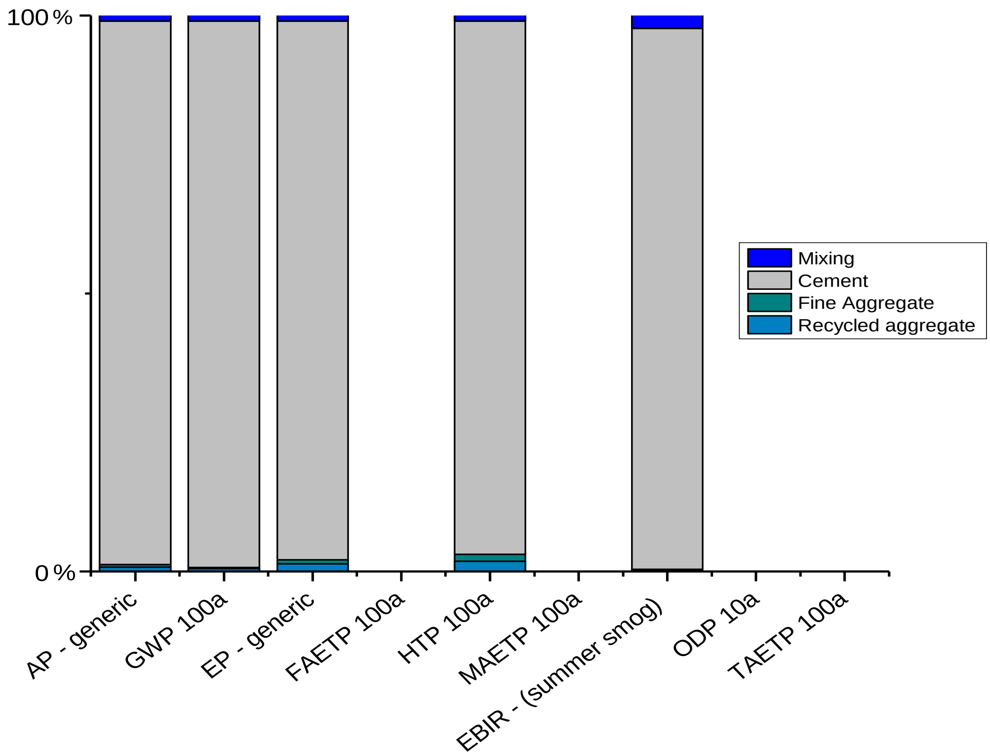

Figure 15. Contribution Analysis for RAC.

Moreover, it is clear from Figure 15 that replacing the coarse aggregate with RA can reduce all environmental impacts. All the impact categories are mostly affected by the use of OPC cement. The lesser contribution of RA to LCIA categories is due to the elimination of mining activity and a lesser transportation distance [21,23,32]. The fine aggregate has the lowest contribution due to its source from the riverbed. Its impact on the LCIA categories mostly depends on the transportation activity. Furthermore, the production of OPC concrete and the RAC mixture shows the lowest impact on the impact categories FAETP, MAETP, and TAETP. This is due to presence of less water emissions, due to its ingredients' activities and production.

The contribution analysis for the GPC and RAGC mixtures is presented in Figures 16 and 17, respectively. For the GPC, the contribution of coarse aggregate, fine aggregate, sodium hydroxide, sodium silicate, and mixing to all LCIA categories is checked. These contributions are checked to predict and verify which ingredient impacts and contributes to the four different concrete mixtures. It is noticed, from Figure 16, that the presence of activators has a higher contribution than the aggregates. The contribution of silicate and hydroxide sources is because of the presence of separate manufacturing processes. Each activator requires considerable chemicals and products for their manufacturing, which leads to higher GHG emissions, along with emissions of certain elements and the addition of chemicals to water systems [9,33]. From Figure 17, it is represented that sodium hydroxide had the highest contribution to all LCIA categories, followed by sodium silicate and coarse aggregate. This contribution depends on the inventory data of the hydroxide and silicate source. The inventory data for sodium hydroxide are based on the chlor-alkali electrolysis method through a membrane cell. In addition, the contribution of coarse aggregate to the impact category of POF—summer smog is higher in both the GPC and RAGC mixtures. This contribution is due to the production of oxides of nitrogen and NMVOC in coarse aggregate manufacturing.

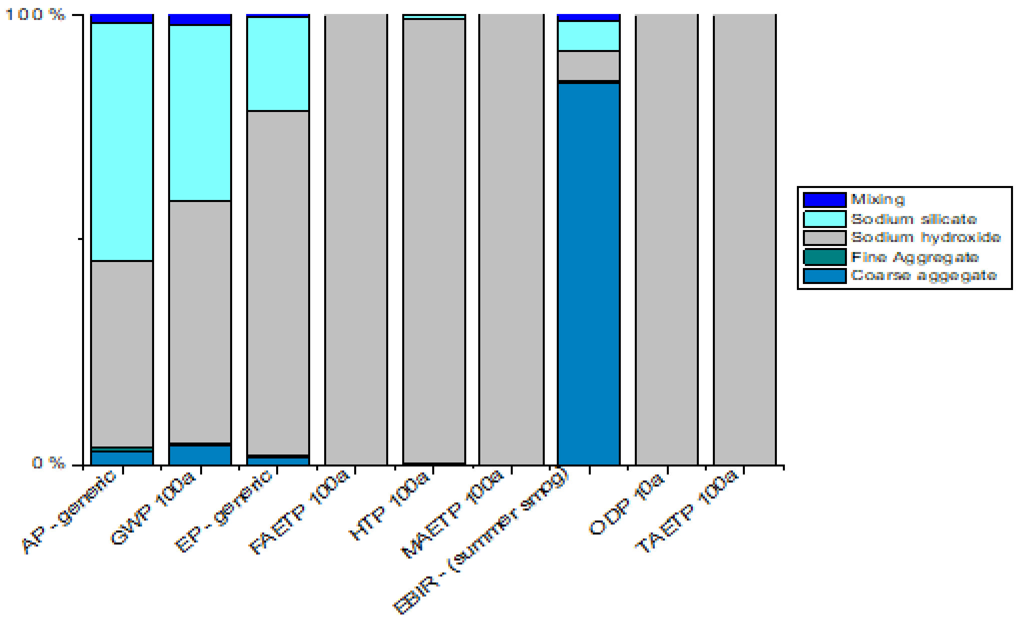

Figure 16. Contribution Analysis for GPC.

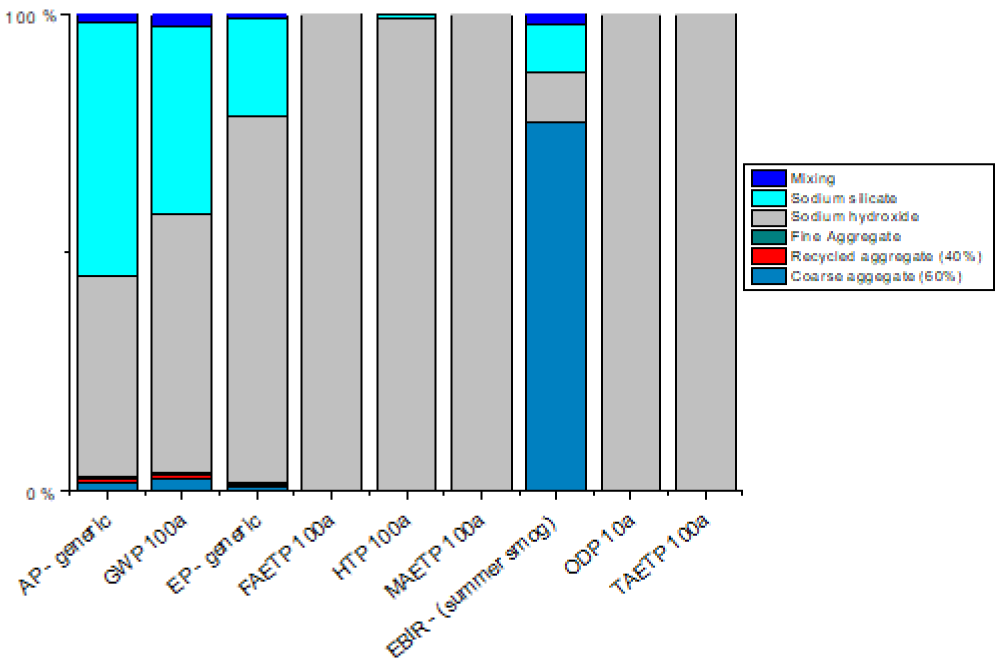

Figure 17. Contribution Analysis for RAGC.

4. Conclusions and Recommendations

Based on the LCA analysis of OPC concrete, the RAC, and the RAGC mixtures, the following conclusions can be drawn:

- A questionnaire survey was conducted to calculate the production and transportation energy of all products of concrete mixtures per kilogram. It is reported from the survey that the total energy (the sum of electric, coal, and transportation energy) required for one kilogram of cement is 2.973 MJ. However, the total energy required for coarse aggregate (the sum of mining, crushing, and transportation energy) and RA (the sum of crushing and transportation energy) are 0.0154 MJ and 0.00834 MJ, respectively. The total energy required for sand production and transportation is 0.0136 MJ;
- A LCA analysis was conducted using OpenLCA software with the aid of the CML 2001 baseline method. Nine different impact categories were analyzed and compared for each mixture in order to evaluate the best mixture for the environment. On the basis of the LCA analysis, it is concluded that OPC in concrete mixtures is the major contributor to the production of negative environmental impacts;
- The use of aggregates also contributes to different environmental impacts, such as GWP, EP, ADP, and POF. The use of RA in both RAC and RAGC mixtures help to reduce the overall environmental impacts. However, the use of RA in concrete mixtures depends on the transportation distances;
- The inclusion of FA as an aluminosilicate in GPC concrete reduces some of the environmental impacts, such as GWP, ADP, and photochemical oxidation. However, the use of alkaline activators, such as sodium silicate and sodium hydroxide, is a major contributor to other environmental impacts, such as FAETP, TAETP, MAETP, ODP, and HTP. Hence, it is important to select the suitable and sustainable manufacturing method for alkaline activators;
- The use of GPC and RAGC mixtures is a more suitable option for reducing the GWP produced due to normal concrete cement. It is concluded that use of GPC lowers the GWP impact up to 57.34%, when compared to OPC concrete. However, categories other than GWP are affected by use of GPC mixtures;
- The use of an alkaline activator is a major contributor to environmental impacts, both in the case of GPC and RAGC. Hence, it is important to select the appropriate source of alkaline activators to be used in the GPC mixture. If the sodium hydroxide is taken

from the seabed, or the sodium silicate is taken from any sustainable source, then the overall environmental impacts of GPC mixtures can be reduced.

However, this study recommends the following future research:

- Research on generating and collecting the LCI data for condition of Pakistan
- The comparison of GPC and RAGC concrete at different percentages of RA
- The comparison of concrete mixtures by using different impact assessment methods
- The investigation of LCA of GPC mixtures by using different manufacturing processes for the alkaline activators
- The investigation of different transportation scenarios while comparing different mixtures of concrete
- The use of normalization and weighting set analysis after the comparison of different concrete mixtures

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Abbreviations

ADP	Acidification Potential
CFC	Chlorofloro Carbons
CML	Centrum voor Milieukunde Leiden
CO	Carbon Monoxide
CO_2	Carbon Dioxide
EPD	Environmental Product Declaration
ER	Environmental Reports
ETP	Eutrophication Potential
EBIR	Equal Benefit Incremental Reactivity
FA	Fly Ash
FAETP	Freshwater Aquatic Ecotoxicity Potential
GGBFS	Ground Granulated Blast Furnace Slag
GHG’s	Greenhouse Gases
GPC	Geopolymer Concrete
GWP	Global Warming Potential
HTP	Human Toxicity Potential
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
MAETP	Marine Aquatic Ecotoxicity Potential
MK	Metakaolin
MIR	Maximum Incremental Reactivity
NO_x	Nitrogen Oxides
NMVOC	Volatile Organic Compounds
PM	Particulate Matter
MOIR	Maximum Ozone Incremental Reactivity
OPC	Ordinary Portland cement

POCP	Photochemical Ozone Creation Potential
RA	Recycled Aggregate
POF	Photochemical Oxidant Formation
RAC	Recycled Aggregate Concrete
SF	Silica Fume
SO_x	Sulphur Oxides
RAGC	Recycled Aggregate Geopolymer Concrete
SETAC	Society of Environmental Toxicology and Chemistry
GWP-100a	100-year Global warming potential
TAETP	Terrestrial Aquatic Ecotoxicity Potential
UNEP	United Nations Environmental Program
ISO	International Organization for Standardization
TRACI	Tool for Reduction and Assessment of Chemical and other Environmental impacts

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