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Environmental Evaluation of Concrete Containing Recycled and By-Product Aggregates Based on Life Cycle Assessment

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Abstract: This study aims to compare the potential environmental impact of the manufacture and production of recycled and by-product aggregates based on a life cycle assessment and to evaluate the environmental impact and cost when they are used as aggregates in concrete. To this end, the six potential environmental impacts (i.e., abiotic depletion potential, global warming potential, ozone-layer depletion potential, acidification potential, photochemical ozone creation potential, and eutrophication potential) of the manufacture and production of natural sand, natural gravel, recycled aggregate, slag aggregate, bottom ash aggregate, and waste glass aggregate were compared using information from life cycle inventory databases. Additionally, the environmental impacts and cost were evaluated when these aggregates were used to replace 30% of the fine and coarse aggregates in concrete with a design strength of 24 MPa. The environmental impact of concrete that incorporated slag aggregate as the fine aggregates or bottom ash aggregate as the coarse aggregates were lower than that of concrete that incorporated natural aggregate. However, concrete that incorporated bottom ash aggregate as the fine aggregates demonstrated relatively high environmental impacts. Based on these environmental impacts, the environmental cost was found to range from 5.88 to 8.79 USD/m^3.

Keywords: environmental evaluation; environmental impact; environmental cost; concrete; recycled aggregate; by-product aggregate; life cycle assessment

1. Introduction

Aggregates are important resources that account for 60–80% of the volume of concrete, and there is a continuously increasing demand for them. The supply and demand of aggregates, however, has been an important discussion point in the construction industry due to the management and regulation of the collection of natural aggregate for environmental conservation purposes in many countries. To address this supply and demand problem, the concrete industry has made considerable efforts to research and develop new concrete that incorporates recycled or by-product aggregate to replace some of the natural aggregate, while still ensuring the same level of quality (e.g., compressive strength and durability) associated with ordinary concrete that incorporates natural aggregate [1,2]. As a result of such research, the application of recycled aggregate extracted from waste concrete has been expanded from its use as a roadbed material to being included in major parts of structures [3–5]. Additionally, studies have actively been conducted to evaluate the performance of slag aggregate, bottom ash aggregate, waste glass aggregate, recycled rubber aggregate, and reclaimed asphalt pavement aggregate, which are recycled and by-product aggregates [6–12].

Guo et al. [6] examined the durability of concrete mixed with recycled aggregate, examining properties such as impermeability, chloride penetration resistance, carbonation resistance, frost resistance, and the alkali-silica reaction. They concluded that the durability of recycled aggregate concrete is mainly affected by the adhered mortar of recycled aggregate, and incorporation of a mineral admixture or using recycled aggregate originating from higher-strength concrete can minimize the durability problem in recycled aggregate concrete. Xuan et al. [7] evaluated various mechanical properties of concrete mixed with carbonated recycled concrete aggregate (RCA), and drew the replacement percentage of natural aggregates by the carbonated RCAs can be increased to 60% with an insignificant reduction in the mechanical properties of the new concrete. Wang et al. [8] proposed an eco-friendly method with acetic acid solution of improving the quality of recycled aggregate, and showed the RCAs can enhance the compressive strength of the concrete at 28 days up to 25%. Kumar et al. [9] conducted research on the utilization of high-performance concrete of 60 MPa in which recycled aggregate was used as both fine and coarse aggregate. Wang et al. [10] evaluated the mechanical strength and durability of concrete mixed with slag and natural aggregates, and they found that steel slag replacement increases the connected porosity and the water permeability, and improves the carbonation resistance and abrasion resistance. Singh et al. [11] examined various physical properties of concrete that incorporated bottom ash as a fine aggregate, and found low quantity of coal bottom ash has the potential to replace the fine aggregates without compromising the performance of the concretes. Park et al. [12] conducted an experimental study in which they assessed the hazards and mechanical properties associated with concrete that incorporated bottom ash as a coarse aggregate. They obtained a result that the soundness and resistance to abrasion of coal bottom ash coarse aggregate were satisfied according to the standard of coarse aggregate for concrete. The result of the leaching test for coal bottom ash coarse aggregate and porous concrete produced with these coarse aggregates, it was satisfied with the environmental criteria. In addition, studies related to various recycled and by-product aggregates have actively been conducted [13–15]. These previous studies are significant in that they inspired technologies that enabled the incorporation of recycled and by-product aggregates into concrete through the analysis of their physical properties.

Environmental impact assessment-based research aimed at identifying the potential environmental impact of each aggregate in advance must also be conducted to determine the applicability of recycled and by-product aggregates [16–18]. Colangelo et al. [19] evaluated different kinds of concrete containing waste as an aggregate based on life cycle assessment (LCA) and concluded the recycled aggregate that had the least adverse impact on the environment was blast furnace waste. Hossain et al. [20] conducted a LCA of aggregate production from recycled waste materials and virgin sources and, concluded that compared with natural coarse aggregates, recycled coarse aggregates produced from construction and demolition waste reduce 65% greenhouse gases (GHGs) emission with a saving of 58% non-renewable energy consumption. Meanwhile, compared with the production of natural fine aggregates from river sand, producing recycled fine aggregates from waste glass saves 54% energy consumption and reduces GHGs and SO_{2eq} emissions by 61% and 46%, respectively. Shi et al. [21] evaluated the sustainability, including the economic impact, the social impact, and the environmental impact, of a RCA-based portland cement concrete (RCA-PCC) pavement and a plain portland cement concrete (PCC) pavement, and concluded that although the RCA-PCC pavement is slightly less sustainable in the use phase due to its rougher pavement surface compared to plain PCC pavement, the RCA-PCC pavement is generally more environmentally and socially friendly due to less consumption of virgin aggregate in the materials production and construction phase. They also evaluated the sustainability of reclaimed asphalt pavement (RAP) in PCC, and among three pavements, including a single-lift pavement made of plain PCC slab, a single-lift pavement made of RAP-PCC slab, and a two-lift concrete pavement, the two-lift construction using RAP-PCC in the bottom lift demonstrated could have the highest positive impacts from environmental and social perspectives [22]. These previous studies are essential in that they evaluated the environmental impacts and sustainability to utilize recycled and by-product aggregates into concrete. Studies involving environmental impact assessments of various recycled and by-product aggregates, however, are still insufficient in terms of scale and depth [23–26]. In particular, research involving LCAs of concrete has become more sophisticated and its scope has been expanding of late. Therefore, research involving the environmental impact assessment of recycled and by-product aggregates, which has usually been conducted using simplified methods or not sufficiently considered in previous studies, is even more urgently required [27–31].

This study thus aims to compare the potential environmental impact of recycled and by-product aggregates based on LCA, and to evaluate the environmental impact and cost when they are used as aggregates in concrete.

2. Materials

2.1. Aggregates

Table 1 shows the life cycle inventory database (LCI DB) information for the natural, recycled, and by-product aggregates that were selected in this study. Here, LCI DB refers to a database that systematically lists all input resources, energy, and minerals in the system boundary set according to the use and characteristics of the products as well as the waste discharged into the environment, including air and water emissions. The LCI DB was used as basic data for conduction of the LCA [32].

Table 1. LCI DB Information for the Natural, Recycled, and By-product Aggregates.

Classification	Functional Unit	System Boundary	Constructed Year	Source
Sand	m^3	Cradle to Gate	2005	KICT LCI DB [1] [33]
Gravel	m^3	Cradle to Gate	2005	KICT LCI DB [1] [33]
Recycled Aggregate	kg	Cradle to Gate	2010	Korean LCI DB [2] [32]
Slag Aggregate	kg	Cradle to Gate	2018	ÖKOBAUDAT [3] [34]
Bottom Ash Aggregate	kg	Cradle to Gate	2018	ÖKOBAUDAT [3] [34]
Waste Glass Aggregate	kg	Cradle to Gate	2018	ÖKOBAUDAT [3] [34]

[1] KICT LCI DB: National DB on Environmental Information of Building Materials by the Korea Institute of Civil Engineering and Building Technology. [2] Korean LCI DB: Life cycle inventory database by the Ministry of Environment of South Korea. [3] ÖKOBAUDAT: Standardized database for ecological evaluations of buildings by the Federal Ministry of the Interior, Building and Community of Germany.

In this study, the National DB on Environmental Information of Building Materials compiled by the Korea Institute of Civil Engineering and Building Technology (KICT) [33] was used as the LCI DB for sand and gravel, which are natural aggregates. Sand means an aggregate with a diameter of less than 5 mm and used the LCI DB allocated by production volume for riverbed sand, seabed sand, crushed sand, and land sand data produced in Korea. Gravel is an aggregate with a diameter of not less than 5 mm and not more than 25 mm and is used the LCI DB for the crushed gravel. For the recycled aggregate, the Korean LCI DB, compiled by the Ministry of Environment (ME) of South Korea [32], was used. Recycled aggregate is an aggregate extracted from waste concrete and used in concrete, road construction, embankment, and cover construction, and selected the LCI DB for the recycled aggregate can be used for regardless of fine recycled aggregate and coarse recycled aggregate. For the slag, bottom ash, and waste glass aggregates, the German ÖKOBAUDAT DB [34] was used because there was no official LCI DB that contained the relevant information and that had been compiled in South Korea. The LCI DB of slag aggregate and bottom ash aggregate is for slag-tap granulate and a solid type dispersal of residue that is generated inevitably during the combustion of coals or lignites, respectively. The LCI DB of waste glass aggregate is for an expanded glass granulate with the main material as waste glass.

2.2. Concrete Mixture Proportions

Table 2 shows the concrete mixture proportions that were evaluated in this study. A total of seven evaluation targets were set by classifying the types of recycled and by-product aggregates. All concrete mixture proportions contain 30% substituted aggregate based on a concrete mix with a design strength of 24 MPa. These concrete mixture proportions were collected through existing research studies [35–41] and all of the proportions of compressive strength as of 28 days were satisfied with the design strength of 24 MPa. Table 3 shows the physical properties of the materials used in the concrete mixture proportions of existing studies.

Table 2. Concrete Mixture Proportions of Evaluation Targets.

Target	W [1] (kg/m^3)	C [2] (kg/m^3)	Fine Aggregate (kg/m^3)					Coarse Aggregate (kg/m^3)			Chemical Admixtures		Source
			NA [3]	RA [4]	SA [5]	BA [6]	GA [7]	NA [3]	RA [4]	BA [6]	kg/m^3	Type	
Std.	180	370	814	0	0	0	0	1001	0	0	2.22	SP [8]	Cho [35]
F-R30	148	321.3	642	252	0	0	0	962	0	0	1.51	AE [9]	Kim et al. [36]
F-S30	180	360	602	0	258	0	0	904	0	0	1.224	WR [10], AE [9]	Park et al. [37,38]
F-B30	180	400	490	0	0	139	0	1110	0	0	2.4	WR [10]	Lee et al. [39]
F-W30	180	370	569.8	0	0	0	244.2	1001	0	0	2.22	SP [8]	Cho [35]
C-R30	169	305	856	0	0	0	0	647	278	0	2.135	SP [8]	Han et al. [40]
C-B30	152	347	823	0	0	0	0	717	0	285	1.176	SP [8]	Kim [41]

[1] Water. [2] Ordinary Portland Cement. [3] Natural Aggregate. [4] Recycled Aggregate. [5] Slag Aggregate. [6] Bottom Ash Aggregate. [7] Waste Glass Aggregate. [8] Superplasticizer. [9] Air Entraining Agent. [10] Water Reducing Agent.

Table 3. Physical Properties of the Materials used in the Concrete Mixture Proportions.

Classification			Std. and F-W30	F-R30	F-S30	F-B30	C-R30	C-B30
Cement		Density (g/cm^3)	3.15	3.15	3.15	3.15	3.15	3.14
		Blaine (cm^2/g)	3450	3602	3450	3266	3390	3200
Aggre-gate	NFA [1]	Density (g/cm^3)	2.60	2.58	2.61	2.59	2.53	2.63
		Absorption Ratio (%)	2.40	0.92	1.57	2.33	0.46	1.50
	NCA [2]	Density (g/cm^3)	2.65	2.60	2.63	2.72	2.59	2.75
		Absorption Ratio (%)	0.6	0.67	0.36	1.32	0.58	1.00
	RBA [3]	Aggregate Type	Waste Glass Aggregate	Recycled Aggregate	Slag Aggregate	Bottom Ash Aggregate	Recycled Aggregate	Bottom Ash Aggregate
		Density (g/cm^3)	2.50	2.51	2.62	1.70	2.55	2.30
		Absorption Ratio (%)	1.13	2.68	3.49	-	3.00	3.30
Chemical Admixtures			Naphthalene Sulfonic Acid	Polycarbonate	Polycarbonate	Naphthalene Polymer	Polycarbonate	Naphthalene Polymer
Source			Cho [35]	Kim et al. [36]	Park et al. [37,38]	Lee et al. [39]	Han et al. [40]	Kim [41]

[1] Natural Fine Aggregate. [2] Natural Coarse Aggregate. [3] Recycled or By-product Aggregate.

3. Methods

3.1. Environmental Impact of Aggregates

Information on various inputs and emissions that are compiled in the LCI DB can be evaluated in terms of various environmental impact categories via the application of the life cycle impact assessment methodology. In other words, information on resources, energy, and minerals available in the LCI DB is used to calculate the abiotic depletion potential (ADP) among the various environmental impacts. In addition, air emissions are used to calculate global warming potential (GWP), ozone-layer depletion potential (ODP), acidification potential (AP), and photochemical ozone creation potential (POCP), while water emissions are used to calculate the eutrophication potential (EP). ADP can lead to destruction of the balance in the ecosystem due to excessive resource collection and consumption, while GWP can result in abnormal weather phenomena related to a rise in the average surface temperature of the earth. ODP can cause an increase in ultraviolet radiation due to the destruction of the atmospheric ozone layer, while AP is associated with environmental conditions leading to the ocean and soil becoming more acidic. POCP is associated with smog phenomena that can cause damage to human health and the loss of ecosystems, as in crop growth inhibition. EP is associated with an abnormal increase in the amount of nutrients in terrestrial and aquatic environments that can cause phenomena such as red tides.

In this study, the six environmental impacts (ADP, GWP, ODP, AP, POCP, and EP) associated with each aggregate as provided by ezEPD [42], a program for environmental product declaration from the Korea Environmental Industry & Technology Institute, and the German ÖKOBAUDAT [34] DB were compared based on the LCI DB aggregate information presented in Table 1. In this instance, for a simple comparison of the environmental impact of each aggregate, mass in kg was used as the reference unit for sand and gravel to reflect the average unit volume weight of aggregates (1750 kg/m^3).

3.2. Environmental Impact of Concrete

The environmental impact of concrete can be calculated by summation of the product of the input amount of each raw material that constitutes the concrete and its environmental impact factor as shown in Equation (1). The six environmental impacts of the seven evaluation targets were evaluated using the mixture proportions shown in Table 2 along with the environmental impact factors associated with each material as shown in Tables 1 and 4. In this instance, the Korean LCI DB compiled by the ME [32] was used for water and ordinary Portland cement, and the LCI DB compiled by Hanyang University (HYU) in South Korea [43] was utilized for the superplasticizer. Because there was no official LCI DB, the LCI DB for air entraining agent and water reducing agent was used in substitution as the LCI DB for the superplasticizer, constructed by HYU.

$$EI_i = \Sigma(Q_j \times EF_{i,j}) \quad (1)$$

where EI_i is the environmental impact evaluation result for the environmental impact category (i). Q_j is the input amount of raw material (j) and $EF_{i,j}$ is the environmental impact factor of the environmental impact category (i) for raw material (j).

Table 4. LCI DB Information for Water, Ordinary Portland Cement, and Superplasticizer.

Classification		Water	Ordinary Portland Cement	Superplasticizer
System Boundary		Cradle to Gate	Cradle to Gate	Cradle to Gate
Constructed Year		2013	2003	2015
Source		Korean LCI DB [32]	Korean LCI DB [32]	HYU LCI DB [43]
Environmental Impact Unit	ADP (kg-Sb_{eq}/kg)	1.76×10^{-6}	3.54×10^{-3}	4.45×10^{-5}
	GWP (kg-CO_{2eq}/kg)	1.02×10^{-4}	9.44×10^{-1}	2.05×10^{-3}
	ODP (kg-$CFC11_{eq}$/kg)	2.78×10^{-15}	5.23×10^{-9}	2.17×10^{-11}
	AP (kg-SO_{2eq}/kg)	1.95×10^{-7}	1.00×10^{-3}	5.45×10^{-8}
	POCP (kg-C_2H_{4eq}/kg)	1.64×10^{-9}	6.61×10^{-4}	5.45×10^{-8}
	EP (kg-$PO_4{}^{3-}{}_{eq}$/kg)	3.34×10^{-8}	1.04×10^{-4}	5.21×10^{-7}

ADP: abiotic depletion potential, GWP: global warming potential, ODP: ozone depletion potential, AP: acidification potential, POCP: photochemical ozone creation potential, EP: eutrophication potential.

3.3. Environmental Cost of Concrete

It is difficult to interpret the evaluation results calculated in the various environmental impact categories and to determine their priorities because reference materials are different for each environmental impact category. Therefore, it is important to unify such evaluation results in a scientific way and express them to improve the current understanding. To address this, the concept of environmental cost was applied, in which endpoint level environmental problems caused by various environmental impact categories are listed and the damage scale is converted into a monetary value [44].

The Korean Life Cycle Impact Assessment Method based on Damage-Oriented Modeling (KOLID) [44], a life cycle environmental impact evaluation methodology for end-point level damage calculation developed by ME, was applied to integrate the evaluation results calculated in the six environmental impact categories into environmental cost, and the environmental cost was evaluated using Equation (2). KOLID is a methodology in which the endpoint level damage caused by the six environmental impact categories (GWP, AP, EP, ODP, POCP, and ADP) is identified in terms of 16 categories (that include categories such as cancer, heat stress, infectious disease, malnutrition, and cataract) associated with four protection targets (human health, social assets, biodiversity, and primary production) and the environmental cost is calculated through their marginal willingness to pay (MWTP). Table 5 shows the environmental cost factor associated with each environmental impact category.

$$EC = \Sigma(EI_i \times ECF_i) \tag{2}$$

where EC is the environmental cost evaluation result, EI_i is the environmental impact evaluation result associated with the environmental impact category (i), and ECF_i is the environmental cost factor associated with the environmental impact category (i).

Table 5. Environmental Cost Factor.

Classification	Unit	Environmental Cost Factor (USD/Unit)
ADP	kg-Sb_{eq}	1.78×10^{-2}
GWP	kg-CO_{2eq}	5.16×10^{-3}
ODP	kg-$CFC11_{eq}$	4.43×10^{1}
AP	kg-SO_{2eq}	1.09×10^{1}
POCP	kg-C_2H_{4eq}	2.52×10^{0}
EP	kg-$PO_4{}^{3-}{}_{eq}$	1.93×10^{0}

ADP: abiotic depletion potential, GWP: global warming potential, ODP: ozone depletion potential, AP: acidification potential, POCP: photochemical ozone creation potential, EP: eutrophication potential, United States Dollar (USD) = 1200 Korean Won.

4. Results

4.1. Environmental Impact of Aggregates

Table 5 shows the six environmental impacts associated with each aggregate released by the ezEPD of South Korea [42] and the German ÖKOBAUDAT DB [34]. Figure 1 shows the scale of the difference between the environmental impact of each aggregate and that of gravel, which is a natural aggregate. As can be seen in Table 6 and Figure 1, the environmental impact of recycled aggregate in all of the six environmental impact categories varied from 2.31 (GWP) to 157.71 (ODP) times higher than that of gravel. This appeared to be due to the energy consumption (e.g., electricity and diesel) and the water resource consumption (e.g., industrial water) associated with the process of extracting and processing recycled aggregate, a process that involves crushing waste concrete with equipment such as jaw crushers [24]. This was despite the fact that the environmental impact of waste concrete, which is the raw material of recycled aggregate, is close to zero. However, an environmental impact of zero was associated with slag and bottom ash aggregates. This was because they were classified as simple industrial by-products which did not require separate processing. The environmental impact of waste glass aggregate was smaller than that of gravel in terms of ADP and ODP. However, it was 42.41 (GWP) to 98.10 (EP) times higher in terms of GWP, AP, POCP, and EP. It appears that waste glass aggregate exhibited this environmental impact due to the energy consumed in the selection and processing of the raw materials, even though the environmental impact of the raw materials was close to zero, as with recycled aggregate.

Table 6. Six Environmental Impacts Associated with Each Aggregate.

Classification	ADP (kg-Sb_{eq}/kg)	GWP (kg-CO_{2eq}/kg)	ODP (kg-$CFC11_{eq}$/kg)	AP (kg-SO_{2eq}/kg)	POCP (kg-C_2H_{4eq}/kg)	EP (kg-$PO_4{}^{3-}{}_{eq}$/kg)
Sand	4.98×10^{-6}	2.21×10^{-3}	1.26×10^{-10}	6.29×10^{-6}	1.17×10^{-6}	1.10×10^{-6}
Gravel	1.04×10^{-5}	6.46×10^{-3}	1.75×10^{-11}	1.13×10^{-5}	2.25×10^{-7}	2.10×10^{-6}
Recycled Aggregate	1.00×10^{-4}	1.49×10^{-2}	2.76×10^{-9}	8.54×10^{-5}	1.89×10^{-5}	1.53×10^{-5}
Slag Aggregate	0	0	0	0	0	0
Bottom Ash Aggregate	0	0	0	0	0	0
Waste Glass Aggregate	5.08×10^{-8}	2.74×10^{-1}	2.62×10^{-15}	5.93×10^{-4}	1.35×10^{-5}	2.06×10^{-4}

ADP: abiotic depletion potential, GWP: global warming potential, ODP: ozone depletion potential, AP: acidification potential, POCP: photochemical ozone creation potential, EP: eutrophication potential.

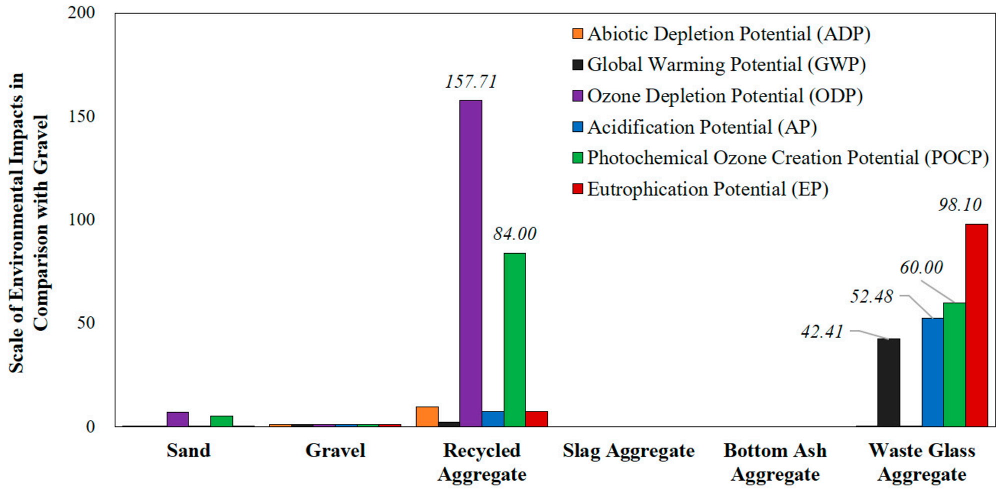

Figure 1. Scale of the Difference Between the Environmental Impact of Each Aggregate and that of Gravel.

4.2. Environmental Impact of Concretes

Table 7 shows the results of the evaluation of the six environmental impacts of the evaluation targets, and Figure 2 shows the environmental impact ratio of each evaluation target in comparison with the standard mixture. According to Table 6 and Figure 2, the environmental impact evaluation results for F-S30 and C-B30, in which some of the fine aggregates were replaced with slag aggregate or coarse aggregates were replaced with bottom ash aggregate, were lower than those of the standard mixture in all of the environmental impact categories. The environmental impact of F-R30 and C-R30 that incorporated recycled aggregate, were lower than those of the standard mixture in all the environmental impact categories except ODP. However, the environmental impact of F-B30 that incorporated bottom ash aggregate as the fine aggregates was higher than that of the standard mixture in all the environmental impact categories.

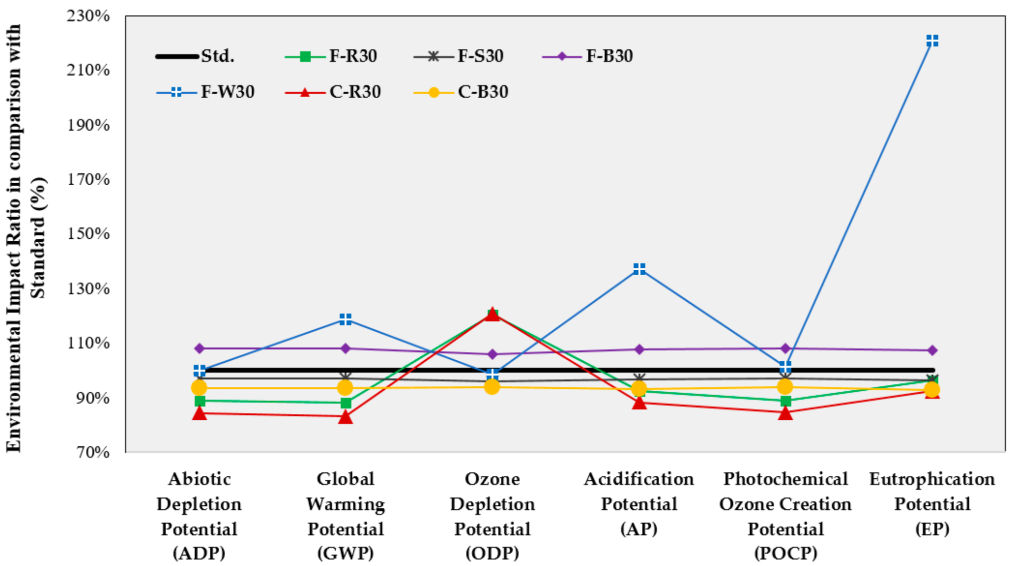

Figure 2. Environmental Impact Ratio of Each Evaluation Target in Comparison with the Standard Mixture.

Table 7. Results of the Evaluation of the Six Environmental Impacts of the Evaluation Targets.

Target	ADP ($kg\text{-}Sb_{eq}/m^3$)	GWP ($kg\text{-}CO_{2eq}/m^3$)	ODP ($kg\text{-}CFC11_{eq}/m^3$)	AP ($kg\text{-}SO_{2eq}/m^3$)	POCP ($kg\text{-}C_2H_{4eq}/m^3$)	EP ($kg\text{-}PO_4{}^{3-}{}_{eq}/m^3$)
Std.	1.32×10^0	3.58×10^2	2.06×10^{-6}	3.86×10^{-1}	2.46×10^{-1}	4.15×10^{-2}
F-R30	1.18×10^0	3.15×10^2	2.47×10^{-6}	3.58×10^{-1}	2.18×10^{-1}	4.00×10^{-2}
F-S30	1.29×10^0	3.47×10^2	1.97×10^{-6}	3.74×10^{-1}	2.39×10^{-1}	4.00×10^{-2}
F-B30	1.43×10^0	3.86×10^2	2.17×10^{-6}	4.16×10^{-1}	2.65×10^{-1}	4.45×10^{-2}
F-W30	1.32×10^0	3.24×10^2	2.02×10^{-6}	5.30×10^{-1}	2.49×10^{-1}	9.15×10^{-2}
C-R30	1.12×10^0	2.98×10^2	2.48×10^{-6}	3.41×10^{-1}	2.08×10^{-1}	3.83×10^{-2}
C-B30	1.24×10^0	3.34×10^2	1.93×10^{-6}	3.60×10^{-1}	2.30×10^{-1}	3.85×10^{-2}

ADP: abiotic depletion potential, GWP: global warming potential, ODP: ozone depletion potential, AP: acidification potential, POCP: photochemical ozone creation potential, EP: eutrophication potential.

In particular, the ADP and POCP of the standard mixture were evaluated to be 1.32×10^0 $kg\text{-}Sb_{eq}/m^3$ and 2.46×10^{-1} $kg\text{-}C_2H_4/m^3$, respectively. All of the evaluation targets exhibited similar evaluation results that ranged from 84.46% (ADP of C-R30) to 107.98% (ADP of F-B30) of those of the standard mixture. The GWP, AP, and EP of the standard mixture were evaluated to be 3.58×10^2 $kg\text{-}CO_{2eq}/m^3$, 3.86×10^{-1} $kg\text{-}SO_{2eq}/m^3$, and 2.46×10^{-2} $kg\text{-}PO_4{}^{3-}{}_{eq}/m^3$, respectively. All the evaluation targets exhibited similar environmental impact evaluation results that ranged from 83.38% (GWP of C-R30) to 107.92% (GWP of F-B30) of those of the standard mixture, except for F-W30 in which some of the fine aggregate was replaced with waste glass aggregate. However, the GWP, AP, and EP evaluation results for F- W30, were very high, ranging from 118.56% (GWP) to 220.61% (EP) of those of the standard mixture.

Among the six environmental impact categories, the ODP evaluation results exhibited the highest correlation with the recycled aggregate. In other words, the ODP evaluation results for F-R30 and C-R30 that incorporated recycled aggregate were 120.36% and 120.75% of that of the standard mixture, respectively. However, the ODP evaluation results for F-W30, which exhibited the highest correlation with the GWP, AP, and EP evaluation results, were slightly lower than that of the standard mixture.

Figure 3 shows the environmental impact ratio with respect to raw materials in the Standard, F-W30, and F-R30 mixtures for the six environmental impact categories (ADP, GWP, ODP, AP, POCP, and EP). According to Figure 3, the environmental impact ratio of aggregate used in the standard mixture that incorporated both sand and gravel, both natural aggregates, ranged from 0.48% (POCP) to 7.23% (EP). However, in the case of F-W30 and F-R30 in which some of the fine aggregate was replaced with recycled and waste glass aggregates, the environmental impact ratio of the aggregate increased, ranging from 1.00% (ADP of F-W30) to 57.95% (EP of F-W30). The environmental impact ratio of cement was found to range from 42.04% (EP of F-W30) to 99.52% (POCP of standard). In most cases, cement exhibited the highest environmental impact ratio among the raw materials used in concrete. The environmental impact ratio of cement and aggregate was found to be 99.9% or higher in all the environmental impact categories, confirming that the environmental impact ratio of water and superplasticizer was quite insignificant.

4.3. Environmental Cost of Concrete

Figure 4 shows the environmental cost evaluation results of the evaluation targets. According to Figure 4, the environmental costs of the evaluation targets ranged from 5.88 USD/m^3 (C-R30) to 8.79 USD/m^3 (F-W30), and that of the standard mixture was calculated to be 6.78 USD/m^3. Environmental costs tended to increase with unit cement volume (F-B30 > F-W30 = Std. > F-S30 > C-B30 > F-R30 > C-R30) in the concrete mixture proportion, while F-W30 rather represented the highest environmental costs, even though less cement was used than F-B30. High environmental costs were observed from F-B30 and F-W30, which exhibited higher EP evaluation results than other mixtures.

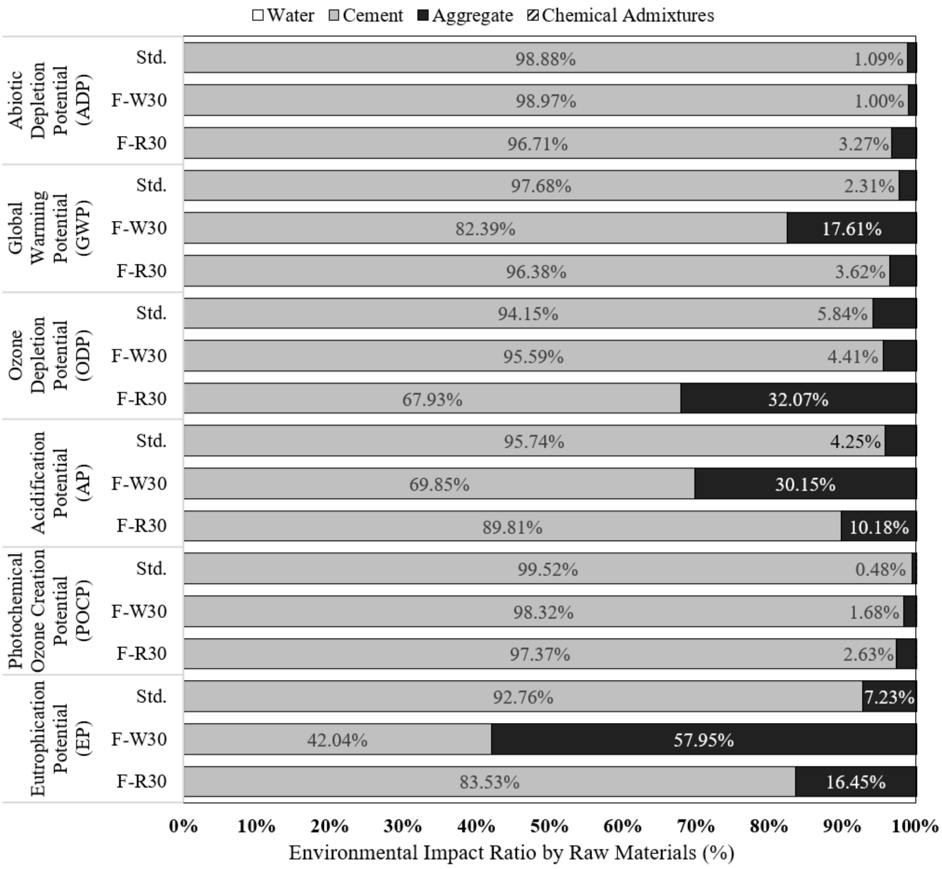

Figure 3. Environmental Impact Ratio with Respect to Raw Materials in the Standard, F-W30, and F-R30 Mixtures.

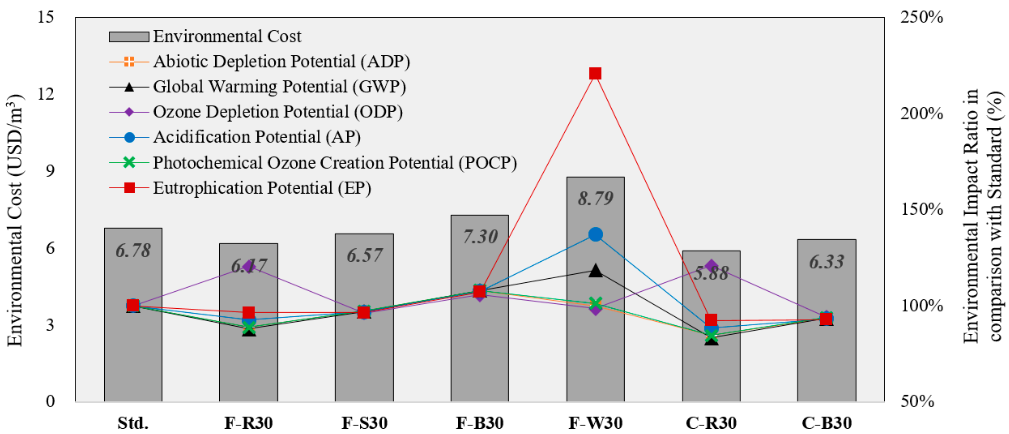

Figure 4. Environmental Cost and Environmental Impact Ratio in Comparison with Standard Mixture.

5. Conclusions

In this study, the potential environmental impacts caused by sand and gravel (natural aggregates) as well as recycled, slag, bottom ash, and waste glass aggregates (recycled and by-product aggregates) were compared based on LCA. In addition, six environmental impacts were evaluated (ADP, GWP, ODP, AP, POCP, and EP) along with the environmental cost that was associated with the aggregates when used in concrete. The results of this study can be summarized as follows:

1. The environmental costs of all the concrete mixture proportions investigated in this study were found to range from 5.88 to 8.79 USD/m^3, while that of the standard mixture was calculated to

be 6.78 USD/m^3. High environmental costs were observed mainly from concrete mixtures that incorporated recycled and waste glass aggregates, which exhibited higher ODP and EP evaluation results than the standard mixture.

2. Concrete that had some of its aggregate contents replaced with slag aggregate as the fine aggregates or bottom ash aggregate as the coarse aggregates exhibited lower environmental impacts than the standard mixture concrete that incorporated only natural aggregate in all environmental impact categories. However, concrete that incorporated bottom ash aggregate as the fine aggregates demonstrated a higher environmental impact than the standard mixture concrete in all the environmental impact categories.
3. The ADP and POCP evaluation results for all the concrete mixture proportions investigated in this study were similar to those of the standard mixture and ranged from 84.46% to 107.98% of the results noted for the standard mixture.
4. The GWP, AP, and EP evaluation results for the concrete mixtures that had some of their aggregate replaced with waste glass aggregate were very high and ranged from 118.56% (GWP) to 220.61% (EP) of those of the standard mixture. However, their ODP evaluation results were slightly lower than that of the standard mixture.
5. The ODP evaluation results exhibited the highest correlation with recycled aggregate. The ODP evaluation results of the concrete mixtures that incorporated recycled aggregate represented about 120% of that of the standard mixture.
6. The environmental impact ratio of aggregate used in the standard mixture ranged from 0.48% (POCP) to 7.23% (EP). However, when some of the fine aggregate was replaced with recycled and waste glass aggregates, the environmental impact ratio of the aggregate increased in the range 1.00% (ADP of F-W30) to 57.95% (EP of F-W30).

Based on the LCI DBs and evaluation range limits applied in this study, some of the recycled and by-product aggregates exhibited higher environmental impacts than natural aggregate in some or most of the environmental impact categories and their environmental costs were also higher. However, because they are fabricated using recycled resources, they are important in terms of conserving the limited amount of available natural resources and in terms of reducing the potential environmental impact and cost associated with waste materials in landfills. Therefore, LCA research that considers the wider environmental impact categories and evaluation ranges of various aggregates, as well as research on concrete and concrete structures that incorporate such aggregates, will be required in the future. It is also deemed necessary to seek methods to reduce various environmental loads, including ODP and EP, through further research concerning the development of recycled and by-product aggregates.

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