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Analysis of Major Environmental Impact Categories of Road Construction Materials

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Abstract: To address the environmental problems associated with construction materials, the construction industry has made considerable efforts to reduce carbon emissions. However, construction materials cause several other environmental problems in addition to carbon emissions and thus, a comprehensive analysis of environmental impact categories is required. This study aims to determine the major environmental impact categories for each construction material in production stage using the life cycle assessment (LCA) technique on road projects. Through the review of life cycle impact assessment (LCIA) methodologies, the abiotic depletion potential (ADP), ozone depletion potential, photochemical oxidant creation potential, acidification potential, eutrophication potential, eco-toxicity potential, human toxicity potential, as well as the global warming potential (GWP) were defined as impact categories. To define the impact categories for road construction materials, major environmental pollutants were analyzed for a number of road projects, and impact categories for 13 major construction materials were selected as mandatory impact categories. These materials contributed more than 80% to the impact categories from an LCA perspective. The impact categories to which each material contributed more than 99% were proposed as specialization impact categories to provide basic data for use in the LCIA of future road projects.

Keywords: construction materials; major environmental impact categories; life cycle assessment; road project

1. Introduction

Concerns over global environmental problems, such as climate change and resource depletion, have been growing worldwide. The United Nations General Assembly in September 2015 included details on climate change and resource depletion in 17 Sustainable Development Goals, and major countries agreed on the efforts to combat climate change by signing the Paris Agreement in December 2015 [1,2]. Accordingly, South Korea set goals to reduce greenhouse gas emissions by 37%, compared to the forecasted emissions in 2030, and is promoting reduction measures, such as improving energy efficiency and increasing the use of waste as an energy resource across industries [3,4]. Each country has made efforts to preserve its environment through direct environmental regulations, such as various product-oriented emission allowance standards, which include integrated product policy (IPP) and ecodesign requirements for energy-using products (EUP), and indirect environmental regulations, such as environmental product declaration (EPD) and renewable energy 100% (RE100). The IPP requires the consideration of the life cycle of a product, and EPD also induces eco-friendly design considered the life cycle environmental impacts. In light of this movement, structures, products, and services in all areas must be developed or operated to minimize environmental loads.

To this end, efficient measures to reduce the emissions of environmental pollutants are required from the construction industry, which consumes energy and resources in large quantities. Social overhead capital (SOC) facilities, such as roads, require strategic support on a national level, and interest in developing technologies to preserve limited resources and reduce environmental loads has been growing in the road construction area. Road construction materials have achieved considerable progress, such as service life extension through durability improvement, recycling of pavement materials, and carbon reducing materials and construction technologies [5–7].

Road construction projects are composites composed of materials, and parts manufactured through various methods, massive resources and energy are required for material production and construction. As for the physical components of the road, such various construction materials are used in the production stage of the infrastructure life cycle process. After such use, they are affected by the life cycle of each road or the life cycle is affected by the service life of each construction material. Basically, the environmental loads, which occur as roads are completed, can be seen as the sum of the environmental loads generated by each construction material.

Therefore, it is necessary to attempt to reduce the environmental loads of each material that constitutes a road to reduce the environmental loads of the road. Entire environmental loads can be reduced considerably if the construction material industry adopts eco-friendly systems, and energy-saving or low-environmental-load construction materials are used at construction sites. To evaluate the environmental load reduction performance, some studies on life cycle assessment (LCA) methods have been conducted, but it is necessary to calculate the environmental loads for each life cycle stage from the material production stage to the construction and operation stage.

Since construction materials involve various conditions throughout the life cycle, technology to systematically assess the impacts of various environmental parameters suitable for the conditions and circumstances of each stage is required. However, basic materials for LCA of construction materials are still insufficient because a life cycle environmental load emission estimation methodology for the construction area has not been established and an environmental impact database with representative features by material has not been constructed. Several studies have been conducted in the road construction area to reduce the environmental impact of construction materials in the material production stage [8–10]. Most studies have focused on the assessment of carbon dioxide (CO_2) emissions; however, emissions of other greenhouse gases (CH_4, N_2O, hydrofluorocarbons, perfluorocarbons, SF_6) also contribute to global warming and climate change. In addition to global warming, other environmental problems such as the depletion of the ozone layer and acid rain should also be considered in the assessment of the environmental impacts of construction materials [11,12]. In the construction industry, swift decision-making must be performed due to the limited road project budget and schedule; thus, it is difficult to examine the environmental impacts of all construction materials.

In the construction material area, active efforts are also being made to minimize environmental load emission and to develop low-carbon and low-energy technologies with high resource recycling rates. However, it is currently difficult to prepare objective environmental load reduction measures through product applicability or reusability improvement by assessing the potential environmental impacts of construction materials and analyzing processes on which environmental load emission is concentrated because there are no detailed procedures and standards for estimating the environmental impacts of the production stage of construction materials. Therefore, it is necessary to provide information on major environmental impact categories that require intensive examination to reduce the environmental load of each input material [13–16].

This is part of a study for the reduction and management of environmental loads during the life cycle of a road project. In this study, major environmental impact categories were selected for each road construction material to reflect the characteristics of the construction materials in production stage using LCA. By reviewing various life cycle impact assessment (LCIA) methodologies, environmental impacts were defined, and criteria for evaluating these impacts were presented. Environmental loads were calculated using the life cycle inventory database (LCI DB), which constructed the environmental loads per functional unit for specific resources as a DB, for the following eight impact categories: global warming potential (GWP), ozone depletion potential (ODP), acidification potential (AP), abiotic depletion potential (ADP), photochemical oxidant creation potential (POCP), eutrophication potential (EP), human toxicity potential (HTP), and eco-toxicity potential (ETP). Based on the analysis of major construction materials used in road construction, impact categories to which such materials contributed more than 95% were proposed as specialization impact categories for each construction material.

2. Literature Review

The LCA is an environmental assessment technique for quantifying the amount of resources input to the production process and for systematically evaluating the impact of pollutant emissions on the environment. The environmental load that quantifies the environmental impact of a product in the LCA is calculated through (1) life cycle inventory analysis (LCI), which quantifies and collects the input resources into the production process and subsequent emissions, and (2) LCIA, which evaluates the contribution of resources and emissions to the impact categories. As the environmental performance of a product may vary depending on the impact category or assessment criteria, it is important to define appropriate impact categories and assessment criteria according to the assessment target and purpose [17–19]. To date, several LCIA methodologies have been developed; each LCIA method defines various impact categories and assessment methods for each category. LCIA is a step to interpret the LCI results more clearly for evaluating the potential environmental impact of the results. It is also a technical process in which the categories of the environmental load substances identified in the LCI are classified by analyzing their environmental impact characteristics, and the results are converted to indicator results by applying indicator values (e.g., characterization, normalization, and weighting values) for evaluation [20–22].

Each country is developing LCIA methodologies according to their environmental goals and ecosystem characteristics (Table 1). Such methodologies have been developed most actively in the Netherlands at government, industrial, and university research institutes [23–26]. In Europe, studies on LCIA methodologies have been mainly conducted at university research institutes. For example, CML 2001 is a method developed by the Center of Environmental Science at Leiden University in the Netherlands. Impact categories can be evaluated using Ecoinvent, which is an internationally used method that provides European and global normalization factors. Eco-indicator 99, which was also developed in the Netherlands in 1999, presents assessment results for resources, ecosystem quality, and human health. In Eco-indicator 99, the effect of inputs or emissions on each of these three items is defined so that the damage for three impact categories can be calculated. EDIP 2003 is a method developed at the Technical University of Denmark in mid-1997 by improving EDIP 97. The method is specific to Europe, except for GWP and ODP, which are considered global impact categories [27–30].

In the United States (US), studies on LCIA and LCA methodologies have been conducted mainly by government agencies. The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) is an environmental impact assessment tool developed by the US Environmental Protection Agency (US EPA) in 2003 to evaluate nine impact categories. The ozone depletion and global warming sectors were developed on a global level, and the other sectors were developed based on the North American source data. TRACI has limitations in evaluating the resource depletion sector. EPS 2000 is a method created in 1990 and 1991 to present environmental loads by converting them into costs. The influence of emissions on each impact category as well as the importance of impact categories defined as cost are presented (five impact categories were considered: human health, ecosystem production capacity, non-biological resources, influence on biodiversity, and cultural and recreational value). The LCIA method established by the Ministry of Trade, Industry, and Energy (MOTIE) and the Ministry of Environment (ME) in South Korea was developed based on CML 2001 of the Netherlands and have great potential for universal applications [31–35].

Table 1. LCIA (life cycle impact assessment) methods.

Method	Nation	Institute	Data Scope	Environmental Impact Category
CML 2001	Netherlands	Center of Environmental Science of Leiden University	Global, Europe	Acidification potential, Climate change, Eutrophication potential, Freshwater aquatic ecotoxicity, Human toxicity, Marine aquatic ecotoxicity, Photochemical oxidation, Resources, Stratospheric ozone depletion, Terrestrial ecotoxicity
EDIP 2003	Denmark	Technical University of Denmark	Europe	Acidification, Terrestrial eutrophication, Photochemical ozone exposure of plants, Photochemical ozone exposure of human beings, Global warming
TRACI	U.S.A.	US EPA	North America	Ozone depletion, Global warming, Acidification, Eutrophication, Photochemical oxidation, Ecotoxicity, Human health
ReCiPe	Netherlands	National Institute for Public Health and the Environment	Global, Europe	Climate change, Stratospheric ozone depletion, Ionizing radiation, Fine particulate matter formation, Photochemical ozone formation, Terrestrial acidification, Freshwater eutrophication, Toxicity, Water use, Land use, Mineral resource scarcity, Fossil resource scarcity
Eco-indicator 99	Netherlands	PRé Sustainability	Global, Europe	Mineral and fossil resources, Ecosystem quality, Human health
EPS 2000	Sweden	IVL	North America, Europe	Life expectance, Severe morbidity, Morbidity, Severe nuisance, Nuisance, Crop growth capacity, Wood growth capacity

3. Methods

3.1. Overview

This study aims to select major environmental impact categories for each construction material to reflect the characteristics of construction materials via LCA. To this end, the LCA was performed in the order of setting the goal and scope, analyzing the LCI, and evaluating the life cycle impact in accordance with ISO 14040 (Figure 1) [36].

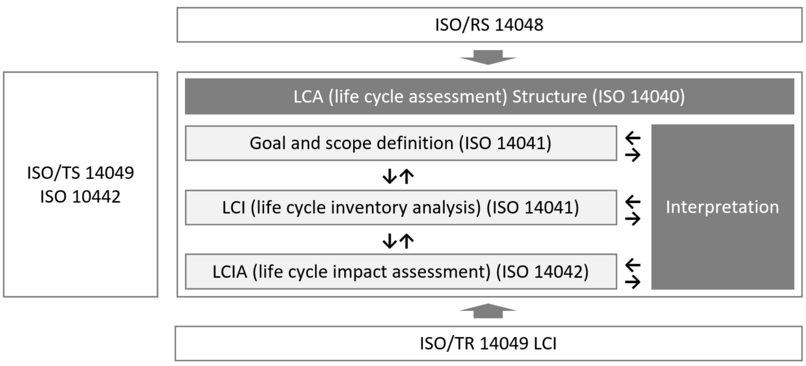

Figure 1. LCA's (life cycle assessment) stages according to ISO 14040.

Goal and scope definition is a step to determine the purpose of performing the LCA and the scope of data collection accordingly. The goal and scope of this LCA were defined as the environmental impact categories specialized in the construction materials through analyzing the impact categories that are emitted in large quantities among impact categories for each construction material in order to induce the selection of the environmental load-reduced construction materials for the road projects. LCI is the step of collecting data based on what is defined in the goal and scope definition. To this end, in this study, the types and quantity data of construction materials for three road projects were collected and the inventory was analyzed only in the production stage among the life cycle system boundaries. LCIA is a step to evaluate the environmental impacts of the evaluated subjects. In this study, the major environmental impact categories were selected by performing the analysis of the environmental impact categories of construction materials input into road projects.

3.2. Goal and Scope Definition

Figure 2 shows the goal and scope of this study based on the theoretical investigation of LCA and impact categories. LCIA was composed of classification, characterization, normalization, and weighting. Roads that play a pivotal role in the transportation system in modern society are composed of three types: road construction, bridges, and tunnels. Road construction refers to a road section completed by performing pavement work on the roadbed mainly created through earthwork. Tunnels are mainly installed in mountain areas, but they are sometimes replaced by the earthworks department depending on the conditions of the site or project. Therefore, it is difficult to judge it as a universal facility applied to all roads. Bridges are structures that are constructed to pass through valleys or rivers, and materials are mainly made of concrete and steel, but the size and structural type applied according to the site conditions are different. Due to these characteristics, it is expected that the environmental impact factors and emission units of the bridge will appear differently depending on the materials used and the applied structural type. Therefore, for bridges and tunnels, it was judged that it would be more reasonable to perform analysis according to materials and types rather than by construction project units, and thus, they were excluded from the scope of this study.

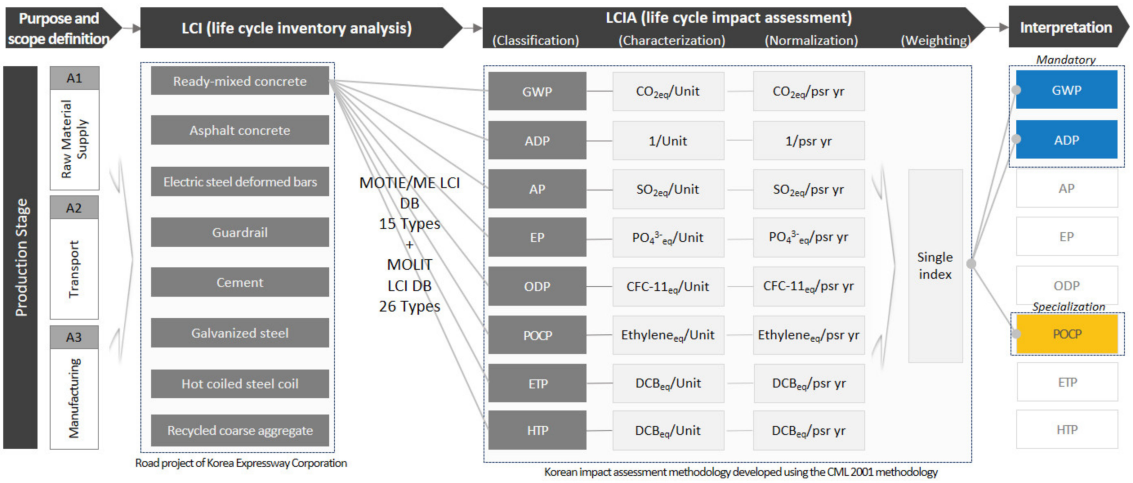

Figure 2. Concept of goal and scope definition.

For the selection of major environmental impact categories for each construction material, construction materials used in the drainage, pavement, and auxiliary tasks, which are the representative tasks of road construction, were analyzed for the material production stage specified in ISO 21930 (Figure 3) and EN15804. In this study, the CML 2001 method was used to define the impact categories and assessment criteria because it can be applied universally as it provides global impacts. Furthermore, the eight impact categories of the previously mentioned CML 2001 methodology were used.

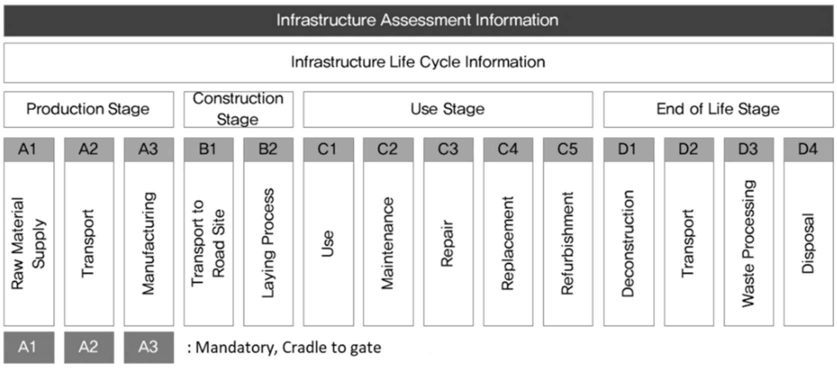

Figure 3. Life cycle stages for the infrastructure assessment in ISO 21930.

3.3. Life Cycle Inventory Analysis (LCI)

LCI is the step of collecting data based on what is defined in the goal and scope definition. For the analysis of the major environmental impact categories of construction materials input into road projects, major construction materials were selected by studying three road project cases, as shown in Table 2, operated by the Korea Expressway Corporation. Among the target cases, projects related to tunnels and bridges were excluded in this study because they cannot be applied universally because of their different sizes and structural types depending on the site conditions. In this study, the material types input to the road projects and their amounts were obtained by analyzing the unit cost calculation data of the three road project cases.

Table 2. Overview of road construction project.

Classification	Project 1	Project 2	Project 3
Project	National road 86 line	National road 33 line	Northern arterial road
Administrative district	Gyeonggi, Namyangju	Gyeongbuk, Goryeong-Sungju	Seoul-Gyeonggi, Namyangju
Design speed	80 km/h	80 km/h	80 km/h
Terrain	Mountainous area	Mountainous area	Downtown area
Length	5.36 km	21.00 km	6.52 km

As the unit weight of the materials, the standard data of the estimates were used. In the case of ready-made products, unit conversion was performed based on their weight. The analysis results showed that major construction materials based on weight are ready-mixed concrete, asphalt concrete, rebar, coarse aggregate, cement, recycled coarse aggregate and concrete products (Table 3).

To calculate the environmental impacts of major construction materials, the Korea National LCI DB (Ministry of Trade, Industry/Energy and Ministry of Environment (MOTIE/ME LCI DB)), which was constructed using the direct estimation method, and the LCI DB of construction materials, which was constructed by investigating the status of the national DB (Ministry of Land, Infrastructure, and Transport (MOLIT LCI DB)) for the environmental impacts of the construction products, were selected. The MOTIE/ME LCI DB and MOLIT LCI DB, to ensure the representativeness of the database for each construction material, quantify inputs and outputs for the production, transportation, and manufacturing stages of raw materials by selecting companies that produce more than 50% of total production volume or, if there is representative production technology, that uses the technology. For this, inputs and outputs were quantified in the raw material supply phase, transportation phase, and manufacturing phase. For the LCI DB of construction materials commonly constructed both in the MOTIE/ME LCI DB and in the MOLIT LCI DB, the MOTIE/ME LCI DB was applied preferentially depending on the Korea LCI DB certification. For the LCI DB of construction materials that are not constructed in the MOTIE/ME LCI DB, the MOLIT LCI was used [6]. Consequently, 41 construction materials were surveyed based on seven categories: 15 materials from the MOTIE/ME LCI DB and 26 from the MOLIT LCI DB as shown in Table 4.

Table 3. Material quantity of road construction project.

No.	Project 1		Project 2		Project 3	
	Materials	Quantity (ton)	Materials	Quantity (ton)	Materials	Quantity (ton)
1	Asphalt concrete	46,525.00	Ready-mixed concrete	165,618.00	Ready-mixed concrete	37,411.80
2	Coarse aggregate	44,053.50	Coarse aggregate	83,295.32	Coarse aggregate	22,365.00
3	Ready-mixed concrete	40,572.00	Asphalt concrete	67,359.00	Asphalt concrete	18,504.00
4	Recycled coarse aggregate	14,356.50	Concrete product	5089.77	Recycled coarse aggregate	6667.50
5	Concrete product	4089.77	Electric steel deformed bars	2449.56	Electric steel deformed bars	4490.16
6	Cement	602.84	Cement	2220.29	Cement	2653.92
7	Granite	416.71	Electro galvanized coil	2106.85	Concrete product	1415.51
8	Asphalt	78.72	Electric steel sections	2006.45	Granite	717.46
9	Electric steel deformed bars	63.79	Asphalt	258.84	Asphalt	101.76
10	Polyethylene pipe	61.85	Polyethylene pipe	123.44	Guard rail	29.76
11	Guard rail	24.80	Guard rail	98.20	Polyethylene pipe	4.80
12	Steel grating	13.14	Steel grating	21.22	Steel grating	3.36
13	Stainless pipe	8.17				

Table 4. LCI DB (life cycle inventory database) of construction materials.

Classification	No.	LCI DB	Functional Unit	Constructed Year	Source	Selection
Ready-mixed concrete	1	Ready-mixed concrete 25-210-12	m^3	2003	MOTIE/ME	Yes
	2	Ready-mixed concrete 25-210-15	m^3	2003	MOTIE/ME	Yes
	3	Ready-mixed concrete 25-240-12	m^3	2003	MOTIE/ME	Yes
	4	Ready-mixed concrete 25-240-15	m^3	2003	MOTIE/ME	Yes
Cement	5	Portland cement type I	kg	2002	MOTIE/ME	Yes
	6	Portland cement type II	kg	2002	MOTIE/ME	Yes
	7	Portland cement type III	kg	2002	MOTIE/ME	Yes
	8	Portland cement type V	kg	2002	MOTIE/ME	Yes
	9	Blast furnace slag cement	kg	2002	MOTIE/ME	Yes
Asphalt concrete	10	Asphalt concrete (base course BB-2)	kg	2013	MOLIT	Yes
	11	Asphalt concrete (surface course WC-2)	kg	2013	MOLIT	Yes
	12	Asphalt concrete (surface course WC-5)	kg	2013	MOLIT	Yes
	13	Hot recycled asphalt concrete (base course BB-2)	kg	2014	MOLIT	Yes
	14	Hot recycled asphalt concrete (surface course WC-2)	kg	2014	MOLIT	Yes
	15	Hot recycled asphalt concrete (surface course WC-4)	kg	2014	MOLIT	Yes
Rebar	16	Electric steel deformed bars	kg	2003	MOTIE/ME	Yes
		Deformed reinforcing steel bar	kg	2003	MOLIT	No
		High-tension deformed reinforcing steel bar	kg	2003	MOLIT	No
Steel	17	Electro galvanized steel sheet	kg	2005	MOTIE/ME	Yes
	18	Steel plates	ton	2005	MOTIE/ME	Yes
	19	Electric steel sections	kg	2002	MOTIE/ME	Yes
Aggregate	20	Crushed sands	kg	2005	MOLIT	Yes
	21	Crushed gravels	kg	2005	MOLIT	Yes
	22	Recycled fine aggregate	kg	2007	MOLIT	Yes
	23	Recycled coarse aggregate	kg	2007	MOLIT	Yes
Steel grating	24	Steel grating I-25-200 mm	kg	2018	MOLIT	Yes
	25	Steel grating I-44-300 mm	kg	2018	MOLIT	Yes
	26	Steel grating I-32-300 mm	kg	2018	MOLIT	Yes
	27	Steel grating I-50 s-400 mm	kg	2018	MOLIT	Yes
	28	Steel grating I-32-400 mm	kg	2018	MOLIT	Yes
	29	Steel grating I-32-500 mm	kg	2018	MOLIT	Yes
	30	Steel grating I-25-500 mm	kg	2018	MOLIT	Yes
Guard rail	31	Guardrail (4 × 350 × 4330 mm)	kg	2018	MOLIT	Yes
	32	Guardrail end treatments(4 × 350 × 765 m)	kg	2018	MOLIT	Yes
HDPE pipes	33	Structured-wall polyethylene pipes (D = 100 mm)	m	2018	MOLIT	Yes
	34	Structured-wall polyethylene pipes (D = 150 mm)	m	2018	MOLIT	Yes
	35	Structured-wall polyethylene pipes (D = 200 mm)	m	2018	MOLIT	Yes
	36	Structured-wall polyethylene pipes (D = 300 mm)	m	2018	MOLIT	Yes
	37	Structured-wall polyethylene pipes (D = 400 mm)	m	2018	MOLIT	Yes
Stainless steel	38	Stainless steel pipe	kg	2005	MOTIE/ME	Yes
Precast concrete	39	Precast concrete product	kg	2019	MOLIT	Yes
Stone block	40	Granite	m^3	2013	MOLIT	Yes
Asphalt primer	41	Asphalt emulsion RC(C)-1,2,3,4	ℓ	2018	MOTIE/ME	Yes

3.4. Life Cycle Impact Assessment (LCIA)

In the LCIA step of the LCA, the impact quantification factor (characterization factor) of each impact category is calculated [37], and the potential contribution to the environmental load is obtained by multiplying the loads (emission or release) of the inventory data classified into each impact category by the characterization factor (Equation (1)).

$$\text{Impact category indicator}_i = \Sigma(E_j \text{ or } R_j) \times CF_{i,j}, \quad (1)$$

where the impact category indicator (characterization value, impact category indicator i) is the indicator value i for the impact category per functional unit; E_j or R_j (emission or release) is emission j or resource consumption j per functional unit; $CF_{i,j}$ is the characterization factor that represents the contribution of emission j or resource consumption j to impact category i.

The characterization factor is a value that represents the potential contribution of emissions to a specific environmental effect. For example, the contributions of NH_3 to AP and EP can be expressed as 0.13 $PO_{4\text{-eq.}}$, which is 0.13 times the contribution of the reference substance (unit) PO_4 for AP, and 1.88 $SO_{2\text{-eq.}}$, which is 1.88 times the contribution of the reference substance SO_2 for EUP. These are referred to as the characterization factors. A high characterization factor means high potential contribution to an environmental effect [38].

When characterization is performed, global characterization factors are applied or local characterization factor models in consideration of regional or temporal characteristics are selected depending on the impact category. This can be determined according to the regional boundary of the environmental effect of the impact category. In the case of global warming impact category, the influence of substances on global warming is not significantly different by region, even though it varies depending on the residence time of the substances in the atmosphere. Therefore, the residence time of the substances (based on 100 years) is determined and the global characterization factor (GWP) is applied to obtain the characterization value of the global warming impact category. In the case of the non-biological resource impact category, if environmental impacts are evaluated for a certain region, biased values can be applied because the reserves and types of such resources are limited depending on the resource depletion or the regional boundaries in South Korea, and they vary globally [39,40]. Therefore, using global values are more appropriate. In the toxicity, eutrophication, and acidification impact categories, however, the characterization factors derived from the target area must be used when inventory data are collected and characterization models are applied because there are large differences in the environmental effects depending on the local environmental conditions.

As the environmental performance of a product may differ depending on the environmental impact assessment categories or assessment criteria, these categories and assessment criteria must be properly defined according to the assessment target and purpose. Various LCIA methods have been developed so far, and each methodology has defined various impact categories and assessment methods for each category. LCIA methods are largely divided into midpoint- and endpoint-level approaches. With the midpoint-level (i.e., problem-oriented) approach, environmental impacts are classified based on environmental problems caused by inputs and outputs, such as global warming, acidification, and eutrophication. With the endpoint-level (i.e., loss-oriented) approach, environmental impacts are classified according to the final damage. These include human damage and ecosystem destruction. These two approaches have different benefits and drawbacks because of their natures. Although midpoint-level methodologies generally include all environmental impacts, the assessment results are difficult to understand. Although the results of endpoint-level methodologies are easy to understand, the inclusion of all losses caused by environmental impacts is not guaranteed. The aim of this study was to define categories for assessing environmental impacts based on a problem-oriented approach for more objective results. The LCIA methods, which had been developed earlier, was applied to this purpose.

The characterization factors and methods that have been used in South Korea are based on the European models or CML 2001 from the Netherlands. Normalization is performed to obtain a more in-depth interpretation of the relative importance of each characterized impact category value or the scale of the indicator results. In other words, the relative contributions (rankings) of impact categories to the environment are evaluated after making the impact category values with different units dimensionless by dividing them by common units, such as the total environmental load, population, and GNP at a certain region and time. When normalization values are obtained, data on the environmental loads of the reference area (assessment area) are required to evaluate the contributions of impact categories by dividing the environmental loads by the reference value. In Europe, the total environmental load values are published each year and used for the LCA [41–45]. In South Korea, however, the total environmental loads generated in South Korea cannot be obtained because pollutant emissions are published only for a few pollutants by several agencies, such as ME [46]. Therefore, to substitute more accurate normalization values (reference values), impact categories that significantly affect the regional environmental characteristics (geographical boundaries), such as eutrophication, acidification, and toxicity, should also use the data collected by each country, which reflect the regional boundaries, when normalization factors are obtained as characterization factors are calculated. In this study, impact categories and assessment criteria were applied based on the CML 2001 method, which can be universally applied, and the Korean impact assessment methodology (Table 5) developed using the CML 2001 method.

Table 5. Impact category of normalization and weighting factor.

Impact Category	Normalization Factor		Weighting Factor
	Value	Unit	Value
ADP	2.49×10^4	g/person-year	2.31×10^{-1}
GWP	5.53×10^6	g $CO_{2\text{-eq}}$/person-year	2.88×10^{-1}
ODP	4.07×10	g $CFC_{\text{-eq}}$/person-year	2.92×10^{-1}
POCP	1.03×10^4	g $C_2H_{4\text{-eq}}$/person-year	6.50×10^{-2}
AP	3.98×10^4	g $SO_{2\text{-eq}}$/person-year	3.60×10^{-2}
EP	1.31×10^4	g $PO_4{}^{3-}{}_{\text{-eq}}$/person-year	3.80×10^{-2}
ETP	1.63×10^3	g $DCB_{\text{-eq}}$/person-year	2.16×10^{-1}
HTP	1.48×10^6	g $DCB_{\text{-eq}}$/person-year	1.05×10^{-1}

4. Analysis of Major Environmental Impact Categories by Construction Material

4.1. Analysis of Impact Category Classification by Construction Material

The classification of data involves the process of classifying and collecting impact substances derived from the LCI DB according to the impact category using the LCIA method, which is based on the existing studies. The classification makes it possible to accurately identify the effect of each substance on the global environment. For example, CO_2, CFC-11, CFC-114, and CFC-12 are among the reference and influence substances that impact global warming, and the results of the classification of ready-mixed concrete 25-240-15 using the national LCI DB are 4.20×10^2 kg-CO_2/m^3, 2.05×10^{-9} kg-CFC-11/m^3, 2.10×10^{-9} kg-CFC-114/m^3, and 4.40×10^{-10} kg-CFC-12/m^3. Table 6 shows the results of the classification of building materials, such as ready-mixed concrete 25-240-15, electric steel deformed bars, and asphalt concrete for base courses (BB-2) using the LCI DB.

Table 6. Classification of LCI DB of building materials (particle).

Classification	Environment	Ready-Mixed Concrete 25-240-15	Electric Steel Deformed Bars	Asphalt Concrete (Base Course BB-2)
CO_2	Air	4.20×10^{2}	3.40×10^{-1}	4.04×10^{0}
CFC-11	Air	2.05×10^{-9}	4.02×10^{-13}	5.87×10^{-13}
CFC-114	Air	2.10×10^{-9}	4.12×10^{-13}	3.08×10^{-11}
CFC-12	Air	4.40×10^{-10}	8.64×10^{-14}	1.97×10^{-13}
Ethane	Air	1.91×10^{-3}	4.34×10^{-7}	7.92×10^{-14}
Ethanol	Air	2.73×10^{-6}	6.19×10^{-10}	2.47×10^{-15}
Halon-1301	Air	3.82×10^{-6}	8.68×10^{-10}	1.25×10^{-11}
NO_2	Air	6.93×10^{-4}	1.38×10^{-6}	7.17×10^{-11}
SO_2	Air	2.67×10^{-1}	4.42×10^{-4}	3.63×10^{0}
PO_4^{3-}	Water	1.76×10^{-4}	4.22×10^{-8}	5.74E $\times 10^{2}$
Crude oil	Soil	4.61×10	2.35×10^{-2}	2.76×10^{2}
Lead (Pb)	Soil	1.39×10^{-6}	2.89×10^{-15}	1.08×10^{-3}

4.2. Analysis of Impact Category Characterization by Construction Material

Although influence substances were identified and connected by impact category through classification, they have different impact quotients. Thus, there are limitations in quantitatively identifying their influence. Therefore, the environmental impact coefficient of construction materials can be quantitatively calculated through characterization, in which the emission of each influence substance is multiplied by the impact quotient of each impact category and the results are added. For example, the impact quotients of CO_2, which is the reference substance of global warming, and CFC-11, CFC-114, and CFC-13, which are the influence substances of global warming, are 1.00×10^{0} kg-CO_2/kg-CO_2, 4.00×10^{3} kg-CO_2/kg-CFC-11, 9.30×10^{3} kg-CO_2/kg-CFC-114, and 8.50×10^{3} kg-CO_2/kg-CFC-13, respectively. When these values are multiplied by the classification results of ready-mixed concrete (25-240-15) (4.20×10^{2} kg-CO_2/m^3, 2.05×10^{-9} kg-CFC-11/m^3, 2.10×10^{-9} kg-CFC-114/m^3, and 4.40×10^{-10} kg-CFC-12/m^3) and added, the environmental impact coefficient of ready-mixed concrete (25-240-15) for global warming (4.29×10^{2} kg-CO_{2eq}/m^3) can be calculated. Main raw materials of ready- mixed concrete include cement, coarse aggregate, fine aggregate, fly ash, and water, and it is produced using electric power. Various emissions and waste materials are generated during its production process. The LCI DB of the ME was used in this study to evaluate the environmental impacts of such byproducts.

The impact categories used to derive the environmental impacts were ADP, GWP, ODP, POCP, AP, EUP, ETP, and HTP. Table 7 shows some of the environmental impact coefficients of construction materials calculated in this study. The characterized environmental impacts of four ready-mixed concrete types, five cement types, and six asphalt concrete types, which have many construction materials of the same type among the seven major construction materials selected in this study, are presented for eight impact categories.

Table 7. Environmental impact coefficient of construction materials.

Classification	Construction Materials	DB	Functional Unit	Environmental Impact Category							
				GWP	ADP	EP	ODP	POCP	AP	HTP	ETP
				$kg\text{-}CO_{2\text{-}eq}$	kg	$kg\text{-}PO_4^{3-}{}_{\text{-}eq}$	$kg\text{-}CFC_{\text{-}eq}$	$kg\text{-}C_2H_{4\text{-}eq}$	$kg\text{-}SO_{2\text{-}eq}$	$kg\ DCB_{\text{-}eq}$	$kg\ DCB_{\text{-}eq}$
Ready-mixed concrete	Ready-mixed concrete 25-21-12	**A**	m^3	4.10×10^{2}	2.04×10^{0}	7.96×10^{-2}	4.65×10^{-5}	9.05×10^{-1}	6.82×10^{-1}	5.57×10	1.59×10^{-3}
	Ready-mixed concrete 25-21-15	A	m^3	4.20×10^{2}	2.05×10^{0}	8.08×10^{-2}	4.61×10^{-5}	9.33×10^{-1}	6.94×10^{-1}	5.52×10	1.57×10^{-3}
	Ready-mixed concrete 25-24-12	A	m^3	4.15×10^{2}	1.66×10^{0}	8.08×10^{-2}	2.34×10^{-5}	9.28×10^{-1}	6.79×10^{-1}	2.88×10	8.04×10^{-4}
	Ready-mixed concrete 25-24-15	A	m^3	4.30×10^{2}	2.08×10^{0}	8.20×10^{-2}	4.59×10^{-5}	9.58×10^{-1}	7.05×10^{-1}	5.50×10	1.57×10^{-3}
Cement	Portland cement type I	A	kg	9.50×10^{-1}	2.70×10^{-3}	1.34×10^{-4}	1.70×10^{-8}	2.43×10^{-3}	1.28×10^{-3}	2.25×10^{-2}	5.94×10^{-7}
	Portland cement type II	A	kg	9.50×10^{-1}	3.00×10^{-3}	9.43×10^{-5}	1.39×10^{-9}	3.26×10^{-5}	1.12×10^{-3}	6.30×10^{-3}	9.20×10^{-8}
	Portland cement type III	A	kg	9.37×10^{-1}	2.93×10^{-3}	9.52×10^{-5}	1.25×10^{-9}	3.10×10^{-5}	1.09×10^{-3}	6.11×10^{-3}	8.70×10^{-8}
	Portland cement type V	A	kg	9.44×10^{-1}	1.49×10^{-3}	9.20×10^{-5}	1.28×10^{-9}	4.10×10^{-6}	5.19×10^{-4}	6.00×10^{-3}	8.44×10^{-8}
	Blast furnace slag cement	A	kg	2.09×10^{-1}	6.48×10^{-4}	6.69×10^{-5}	4.14×10^{-9}	4.52×10^{-4}	5.51×10^{-4}	5.73×10^{-3}	1.44×10^{-7}
Asphalt concrete	Asphalt concrete (base course BB-2)	B	kg	4.11×10^{0}	1.55×10^{-2}	1.68×10^{-5}	0.00×10^{0}	2.93×10^{-3}	1.09×10^{-4}	4.17×10^{-3}	3.68×10^{-8}
	Asphalt concrete (surface course WC-2)	B	kg	3.98×10^{0}	1.54×10^{-2}	1.75×10^{-5}	0.00×10^{0}	2.86×10^{-3}	1.19×10^{-4}	4.15×10^{-3}	3.68×10^{-8}
	Asphalt concrete (surface course WC-5)	B	kg	4.00×10^{0}	1.54×10^{-2}	1.72×10^{-5}	0.00×10^{0}	2.87×10^{-3}	1.19×10^{-4}	4.15×10^{-3}	3.68×10^{-8}
	Hot recycled asphalt concrete (BB-2)	B	kg	1.16×10	4.73×10^{-2}	3.24×10^{-5}	3.62×10^{-8}	6.71×10^{-3}	1.12×10^{-3}	1.10×10^{-1}	1.58×10^{-5}
	Hot recycled asphalt concrete (WC-2)	B	kg	1.19×10	4.85×10^{-2}	4.29×10^{-5}	2.88×10^{-8}	6.89×10^{-3}	1.14×10^{-3}	7.64×10^{-2}	2.41×10^{-5}
	Hot recycled asphalt concrete (WC-4)	B	kg	1.19×10	4.85×10^{-2}	4.29×10^{-5}	2.88×10^{-8}	6.89×10^{-3}	1.14×10^{-3}	7.64×10^{-2}	2.41×10^{-5}
Rebar	Electric steel deformed bars	A	kg	4.38×10^{-1}	1.85×10^{-3}	5.83×10^{-7}	8.68×10^{-9}	3.16×10^{-4}	4.44×10^{-4}	1.72×10^{-2}	2.98×10^{-6}
Aggregate	Crushed sands	B	m^3	5.10×10^{0}	1.79×10^{-2}	5.70×10^{-6}	0.00×10^{0}	3.56×10^{-3}	7.88×10^{-5}	9.32×10^{-4}	0.00×10^{0}
	Crushed gravels	B	m^3	1.13×10	3.98×10^{-2}	1.53×10^{-5}	0.00×10^{0}	7.92×10^{-3}	1.76×10^{-4}	2.07×10^{-3}	0.00×10^{0}
	Recycled fine aggregate	B	m^3	9.98×10^{2}	2.73×10^{0}	1.24×10^{-3}	2.86×10^{-11}	6.92×10^{-1}	4.52×10^{-3}	5.36×10^{-1}	7.12×10^{-6}
	Recycled coarse aggregate	B	m^3	4.49×10	1.25×10^{-1}	5.68×10^{-5}	1.28×10^{-11}	3.14×10^{-2}	3.04×10^{-4}	1.50×10^{-1}	3.18×10^{-6}

Note: The mark in the DB, 'A' is the MOTIE/ME LCI DB; 'B' is the MOLIT LCI DB.

4.3. Analysis of Impact Category Normalization/Weighting by Construction Material

In this study, an integrated factor was calculated by applying the weighting factor of each impact category to consider the relative importance of eight impact categories for each construction material. Normalization (environmental impact on one category is divided by the total environmental impact contributing to the impact category during a certain period) and weighting (the relative importance of the impact categories) were performed. The Global Normalization, Centre of Environmental Science normalization factor and the CML 2001, Center of Environmental Science weighting factor presented in Table 5 were used. For 13 types and 41 construction materials included in the ME LCI DB and the MOLIT LCI DB, impact categories for each construction material were analyzed by applying a cut-off level cumulative weight of 99%. The cut-off criteria presented by ISO 21930 and guidelines on the preparation of building LCA were utilized for the LCA in South Korea. According to the cut-off criteria, the unit process, the substance amount, energy consumption, and environmental significance will be excluded from the study, and substances that contribute more than 99% in terms of mass or environmental relevance among the substances that constitute the assessment target will be included in the LCA. The results are shown in Table 8.

Table 8. Weighting coefficient according to environmental impact categories of construction materials.

Classification	Construction Materials	DB	Environmental Impact Category (%)							
			GWP	ADP	EP	ODP	POCP	AP	HTP	ETP
Ready-mixed concrete	Ready-mixed concrete 25-21-12	A	41.65	36.92	0.45	0.65	11.14	1.20	7.71	0.27
	Ready-mixed concrete 25-21-15	A	42.04	36.55	0.45	0.64	11.32	1.21	7.53	0.27
	Ready-mixed concrete 25-24-12	A	46.98	33.48	0.51	0.36	12.73	1.34	4.44	0.15
	Ready-mixed concrete 25-24-15	A	42.27	36.42	0.45	0.62	11.41	1.20	7.36	0.26
Cement	Portland cement type I	A	53.10	26.88	0.42	0.13	16.46	1.24	1.71	0.06
	Portland cement type II	A	62.42	35.11	0.35	0.01	0.26	1.28	0.56	0.01
	Portland cement type III	A	62.65	34.90	0.35	0.01	0.25	1.27	0.56	0.01
	Portland cement type V	A	76.59	21.53	0.42	0.01	0.04	0.73	0.66	0.01
	Blast furnace slag cement	A	52.10	28.78	0.93	0.14	13.65	2.39	1.95	0.06
Asphalt concrete	Asphalt concrete (base course BB-2)	B	56.81	38.16	0.01	0.00	4.91	0.03	0.08	0.00
	Asphalt concrete (surface course WC-2)	B	56.23	38.75	0.01	0.00	4.90	0.03	0.08	0.00
	Asphalt concrete (surface course WC-5)	B	56.34	38.64	0.01	0.00	4.90	0.03	0.08	0.00
	Hot recycled asphalt concrete (BB-2)	B	55.13	40.04	0.01	0.02	3.86	0.09	0.71	0.13
	Hot recycled asphalt concrete (WC-2)	B	55.23	40.10	0.01	0.02	3.88	0.09	0.48	0.19
	Hot recycled asphalt concrete (WC-4)	B	55.23	40.10	0.01	0.02	3.88	0.09	0.48	0.19
Rebar	Electric steel deformed bars	A	51.89	39.14	0.00	0.14	4.54	0.91	2.77	0.60
Steel	Electro galvanized steel sheet	A	26.85	60.79	0.00	0.05	8.37	1.54	0.99	1.41
	Steel plates	A	30.07	53.20	0.00	0.22	12.18	0.56	3.69	0.09
	Electric steel sections	A	45.92	43.23	0.00	0.35	3.97	0.71	5.35	0.46
Aggregate	Crushed sands	B	58.42	36.60	0.00	0.00	4.95	0.02	0.01	0.00
	Crushed gravels	B	58.41	36.61	0.00	0.00	4.95	0.02	0.01	0.00
	Recycled fine aggregate	B	63.63	30.97	0.00	0.00	5.34	0.01	0.05	0.00
	Recycled coarse aggregate	B	63.09	31.27	0.00	0.00	5.34	0.01	0.29	0.01
Steel grating	Steel grating I-25-200	B	28.63	35.59	0.06	0.61	2.22	4.78	21.57	6.54
	Steel grating I-44-300	B	28.10	35.09	0.06	0.64	2.08	4.48	22.67	6.89
	Steel grating I-32-300	B	27.01	33.75	0.06	0.70	1.80	3.85	25.18	7.65
	Steel grating I-50 s-400	B	28.68	35.67	0.06	0.61	2.23	4.80	21.44	6.52
	Steel grating I-32-400	B	30.32	37.63	0.06	0.51	2.66	5.76	17.70	5.37
	Steel grating I-32-500	B	30.60	37.93	0.06	0.50	2.73	5.91	17.09	5.19
	Steel grating I-25-500	B	29.20	36.33	0.06	0.57	2.37	5.11	20.19	6.16
Guard rail	Guardrail (4 * 350 * 4330 mm)	B	44.30	50.41	0.23	0.05	1.54	1.04	0.79	1.65
	Guardrail end treatments(4 * 350 * 765 m)	B	39.58	53.69	0.45	0.13	1.02	1.39	2.20	1.54
HDPE pipes	Structured-wall PE pipe (D = 100 mm)	B	23.82	71.38	0.27	0.04	3.02	0.44	0.49	0.54
	Structured-wall PE pipe (D = 150 mm)	B	23.78	71.44	0.27	0.04	3.01	0.44	0.49	0.53
	Structured-wall PE pipe (D = 200 mm)	B	23.82	71.39	0.27	0.04	3.01	0.44	0.49	0.53
	Structured-wall PE pipe (D = 300 mm)	B	23.77	71.44	0.27	0.04	3.01	0.44	0.49	0.54
	Structured-wall PE pipe (D = 400 mm)	B	23.74	71.48	0.27	0.04	3.01	0.44	0.49	0.53
Stainless steel	Stainless steel pipe	A	18.76	18.04	0.30	0.99	1.06	0.46	42.17	18.19
Precast concrete	Precast concrete product	B	53.18	35.70	0.37	0.10	1.65	0.13	7.82	1.04
Stone block	Granite	B	36.82	42.60	0.09	0.98	4.24	0.27	13.87	1.12
Asphalt primer	Asphalt emulsion	A	18.62	50.92	0.60	0.81	2.74	1.00	4.49	20.82

Note: The mark in the DB, 'A' is the MOTIE/ME LCI DB; 'B' is the MOLIT LCI DB.

The normalization/weighting reference values were analyzed along with the results applied to the characterization results. The top major environmental impact categories for each construction material were ADP, GWP, and POCP (in descending order) for ready-mixed concrete, and GWP and ADP for cement. Only ordinary Portland cement and blast furnace slag cement exhibited high impact on POCP. The top major environmental impact categories were GWP, ADP, POCP for rebar; and ADP, GWP, POCP for steel; GWP, ADP, POCP for crushed gravels and recycled aggregate. Only electro galvanized steel sheet, steel plates and electric steel sections exhibited high impact on HTP. The top impact categories for steel grating were ADP and GWP, while steel grating exhibited the highest influence on HTP. This result was significantly affected by the use of a coagulant in the hot dip galvanizing process. Those for guard rail were GWP and ADP. HDPE pipes highly influenced ADP, GWP, POCP and ETP in descending order.

The top major environmental impact categories were HTP, GWP, ADP, ETP for stainless steel; and GWP, ADP for precast concrete product; ADP, GWP, HTP for granite stone block. Asphalt primer also showed high impact on ADP and GWP, but HTP exhibited higher environmental impact than GWP because of the use of emulsifying agent during the chemical treatment process. For GWP, which exhibited high unit values in the characterization results for all the construction materials, the values became relatively smaller through normalization due to the large normalization reference value. To determine the specialization impact categories for each construction material, impact categories to which each material contributes more than 99% were derived (Table 9). The impact categories that occupy a weighting factor of 80% or higher for all the construction materials were selected as mandatory impact categories, and those that occupy a weighting factor of 99% or higher, excluding the mandatory impact categories, were proposed as specialization impact categories for each construction material. The mandatory impact categories were GWP and ADP. The specialization impact categories were AP, POCP, and HTP for concrete; POCP for cement; HTP for asphalt; AP for rebar; AP and HTP for steel; and AP, POCP, and HTP for concrete products.

Table 9. Deduction of major environmental impact categories.

Classification	GWP	ADP	EP	ODP	POCP	AP	HTP	ETP
Ready-mixed concrete	●	●		○	●	○	○	
Cement	●	●			○	○	○	
Asphalt concrete	●	●			○			
Rebar	●	●			○	○	○	
Steel	●	●			○		○	
Aggregate	●	●			○			
Steel grating	●	●			○	○	●	○
Guard rail	●	●			○	○	○	○
HDPE pipe	●	●			○		○	○
Stainless steel	●	●		○	○		●	●
Precast concrete	●	●			○		○	○
Stone block	●	●		○	○		●	○
Asphalt primer	●	●		○	○	○	○	●

● Mandatory Environmental Impact Category, ○ Specialization Environmental Impact Category

5. Discussion

The major environmental impact categories for construction materials are shown in Figure 4. The analysis of the impact categories of ready-mixed concrete showed that GWP, ADP and POCP accounted for more than 80%.

As the strength of the ready-mixed concrete increased, GWP, ADP, and POCP also showed an increase, but ADP was inversely proportional to the strength of the ready-mixed concrete. This is because the content of cement generally increases and that of aggregate (gravel and sand) decreases as the strength of the ready-mixed concrete increases. As the content of cement, which has higher environmental impact on GWP, EUP, and POCP than the aggregate, increased, the corresponding environmental impacts also increased. Meanwhile, ADP declined because the amount of aggregates, which has a high environmental impact on ADP, decreased. To analyze the environmental impact characterization values of asphalt concrete, 2.9% virgin asphalt was used relative to the product weight, but virgin asphalt was found to have high environmental impacts on categories of ADP, ODP, and EUP. For six asphalt concrete types, the manufacturing process and the input amount of virgin asphalt exhibited high contribution to GWP and HTP.

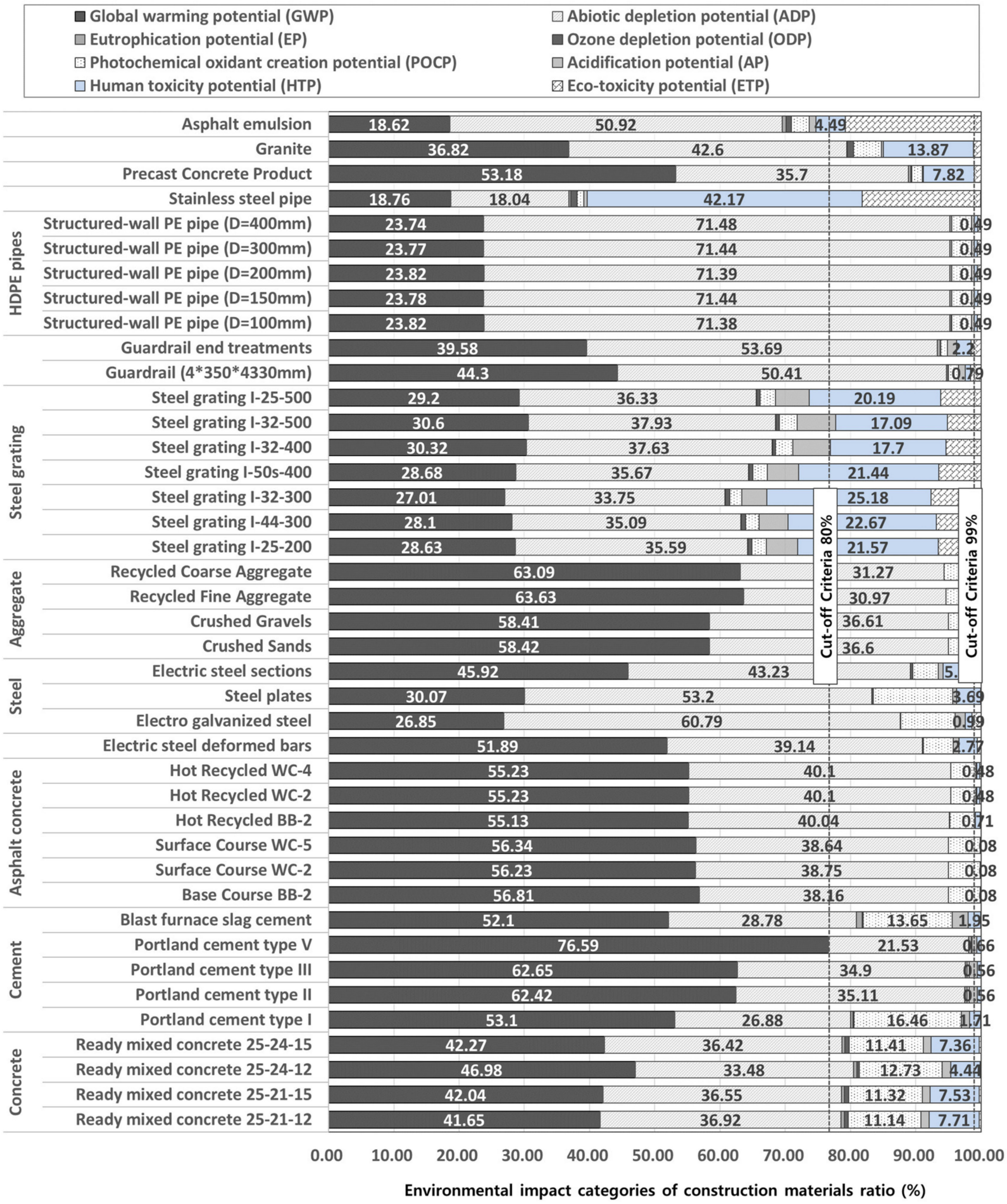

Figure 4. Major environmental impact categories of construction materials.

For Portland cement, the environmental impact contribution to GWP, ADP, and EP showed an increase in the order of Portland cement type III (high early strength cement), Portland cement type V (sulfate-resisting cement), Portland cement type I (ordinary cement), and Portland cement type II (moderate heat cement). This is because the content of belite, which is among the calcium silicates that constitute clinker, generally increases in the same order, but the alite content decreases. Belite is expected to have a higher environmental impact on GWP, ADP and EP than alite. Meanwhile, blast furnace slag cement has a very low environmental impact on GWP and ADP but relatively high environmental impact on ODP and POCP compared to Portland cement. This is because the blast furnace slag, which is added during the production of blast furnace slag cement, has an excellent environmental impact on GWP but high environmental impact on ODP and POCP, compared to the clinker of Portland cement. Therefore, the use of blast furnace slag cement is favorable for GWP and ADP, but its eco-friendliness may vary depending on the impact categories considered during the LCA.

6. Conclusions

This study was conducted to select the major environmental impact categories for each construction material, which reflect the characteristics of construction materials, using the LCIA. The results can be summarized as follows.

- To determine the major environmental impact categories for evaluating the environmental impacts of construction materials and to present assessment methods for each major environmental impact, various impact categories were defined by analyzing the previous studies on LCIA.
- Thirteen major construction materials, including ready-mixed concrete, asphalt concrete and electric steel deformed bars, and 41 types of materials in three road project cases were selected. In addition, eight impact categories, i.e., ozone depletion potential (ODP), abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), photochemical oxidant creation potential (POCP), human toxicity potential (HTP), terrestrial eco-toxicity potential (TETP), and global warming potential (GWP), which is represented by CO_2 emissions, were defined as major environmental impact categories, and assessment criteria for each impact category were presented.
- Impact categories to which all the construction materials contributed more than 80% were selected as mandatory impact categories, and those to which each construction material contributed more than 99% were proposed as specialization impact categories for each construction material.
- The analysis of the environmental impacts calculated in this study showed that the content of cement is the main factor that determines the environmental impact of ready-mixed concrete, and that the contents of alite and belite determine the environmental impact of cement.
- Blast furnace slag cement exhibited a low environmental impact for GWP but high environmental impact for ODP and POCP compared to Portland cement. As eco-friendliness differs depending on the impact category considered, it is deemed necessary to evaluate eco-friendliness in various aspects.
- The impact categories to be evaluated for all the construction materials were GWP and ADP. Specialization impact categories for each construction material were AP and POCP for concrete; HTP for asphalt concrete; AP for rebar; AP and HTP for steel; and EP and AP for concrete products.
- For a more accurate assessment of the environmental impact of construction materials, it is necessary to perform an assessment of various environmental impacts in addition to GWP.

This study can provide basic data for reviewing the environmental properties of construction materials in the planning stage of the road projects. Through this, by quickly grasping the major construction materials subject to review and changes in environmental impacts in the early stages of project execution, delays or cost incurred due to unnecessary trial and error are prevented, and alternative resources or construction methods for eco-friendly construction will be able to facilitate development.

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Nomenclature

ADP	Abiotic Depletion Potential
AP	Acidification Potential
C_2H_4-eq	Equal to Ethylene
CFC-eq	Equal to Chloro Fluoro Carbon
CML	Center of Environmental Science of Leiden University
CO_2-eq	Equal to Carbon Dioxide
DCB-eq	Equal to Dichlorobenzene
EDIP	Environmental Design of Industrial Products
EP	Eutrophication Potential
EPA	Environmental Protection Agency
EPD	Environmental Product Declaration
EPS	Environmental Priority Strategies
ETP	Eco-Toxicity Potential
EUP	Ecodesign Requirements for Energy-Using Products
GHG	Greenhouse Gas
GWP	Global Warming Potential
HTP	Human Toxicity Potential
IPP	Integrated Product Policy
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
ME	South Korea's Ministry of Environment
MOLIT	South Korea's Ministry of Land, Infrastructure, and Transport
MOTIE	South Korea's Ministry of Trade, Industry, and Energy
ODP	Ozone Depletion Potential
$PO_4{}^{3-}$-eq	Equal to Inorganic Phosphate
POCP	Photochemical Oxidant Creation Potential
RE100	Renewable Energy 100%
SO_2-eq	Equal to Sulfur Dioxide
SOC	Social Overhead Capital
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts

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