

Article

Identifying the Major Construction Wastes in the Building Construction Phase Based on Life Cycle Assessments

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Abstract: The purpose of this study was to identify the major wastes generated during the construction phase using a life cycle assessment. To accomplish this, the amount of waste generated in the construction phase was deduced using the loss rate and weight conversions. Major construction wastes were assessed using six comprehensive environmental impact categories, including global warming potential, abiotic depletion potential, acidification potential, eutrophication potential, ozone depletion potential, and photochemical ozone creation potential. According to the analysis results, five main construction wastes—concrete, rebar, cement, polystyrene panel, and concrete block—comprehensively satisfied the 95% cutoff criteria for all six environmental impact categories. The results of the environmental impact characterization assessment revealed that concrete, concrete block, and cement waste accounted for over 70% of the contribution level in all the environmental impact categories except resource depletion. Insulation materials accounted for 1% of the total waste generated but were identified by the environmental impact assessment to have the highest contribution level.

Keywords: major construction wastes; life cycle assessment; construction phase

1. Introduction

In 2015, South Korea attended the 21st Conference of the Parties (COP21) at the United Nations Framework Convention on Climate Change (UNFCCC) held in Paris, France, and declared their Intended Nationally Determined Contributions (INDC) to voluntarily reduce greenhouse gas emissions by 37% by 2030. Meanwhile, the construction industry has been regarded as a key area with excellent potential to reduce greenhouse gases and contribute to achieving the national greenhouse gas reduction goals [1–6]. Since the importance of reducing waste in the construction industry has been recognized, there has been increasing interest in life cycle assessments of environmental impacts spanning from the production and construction phases to the demolition phases. Considering the progression of global warming, reducing the environmental load of the construction sector is essential in decreasing its environmental impact [7–10].

Efforts are actively being made to develop eco-friendly construction production systems that minimize the environmental load from a life cycle perspective by reducing waste and greenhouse gas emissions from buildings [11–13]. Studies on the demolition phase, such as separating demolition items to minimize waste and maximize recycling rates, and establishing databases for waste units,

are conducted within the construction industry. Studies on the construction phase, on the other hand, fail to keep up with the demolition phase due to frequent design changes that make it difficult for the amount of generated waste and environmental load to be controlled [14–16].

In particular, the construction phase prefers discharging its waste altogether rather than separately storing and discharging the waste materials to minimize the disposal costs and clean construction site management of narrow spaces. Mixed construction waste should be separated according to the characteristics of each piece and be accompanied by more appropriate and detailed treatments, such as recycling, incineration, and landfill. When two or more types of construction waste are mixed, the combination is classified as mixed construction waste. According to the Korean Ministry of Environment's guidelines on the standards and methods for the disposal of construction waste, mixed construction waste will have less than a 5% mixture rate of non-flammable and other waste in terms of the weight. However, the amount of mixed waste at the construction site is increasing due to the mixing of small amounts of foreign substances creating large quantities of mixtures, as the method of inspecting construction wastes is only visual. The main reason is that there are few cases where separate discharge obligations are fulfilled at construction sites since supervision and regulation for those failing to discharge separate emissions are not normally carried out [17,18].

The mixed construction waste generated in this way is transported by waste collection and transportation companies, waste intermediate treatment companies, and waste recycling companies. However, regarding mixed construction waste, many types of construction waste are in this mixture, and high-quality construction waste that can be recycled is not completely reclassified and is being landfilled or incinerated [19,20]. This passive classification and management of mixed construction waste at the construction stage, which relies solely on the intermediate waste disposal companies, serves as a factor hindering the efforts to reduce waste at those sites. As a result, it not only lowers the potential for recycling various wastes but also makes it difficult to manage special waste, such as designated wastes. In addition, it is difficult to establish a management plan based on the amount of generated waste and its environmental impact due to the nature of the waste, thus hindering efficient environmental management. Selective waste management during the construction phase will not only contribute to the establishment of an eco-friendly construction production system that minimizes waste and maximizes recycling rates but will also provide economic benefits [21–23].

Therefore, the purpose of this study was to determine the major wastes generated during the construction phase from the perspective of an environmental impact evaluation by applying the life cycle assessment method.

The major construction wastes were determined through a life cycle assessment in two steps: calculating the amount of the generated waste and using that calculation to determine the major construction wastes for six types of environmental impacts. To achieve this, the quantities of generated waste were analyzed using the material loss rates and weight conversion factors. The loss rates were taken from research reports on the standard of estimation for construction projects, construction waste separation, and the generation units published by the Korea Institute of Construction Technology and the Ministry of Land, Infrastructure, and Transport in 2017 [24,25]. The weight conversion factors from the standard of estimation for construction projects were used to standardize the specifications of various materials. The materials requiring specific management were determined based on the calculated amounts of construction waste generated and through a comprehensive analysis of six types of environmental impacts: global warming potential (GWP), abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), ozone depletion potential (ODP), and photochemical ozone creation potential (POCP).

2. Characteristics of Construction Wastes and the Current State of Management

The European Commission report, *Resource Efficiency Opportunities in the Building Sector*, urges the reduction of environmental impacts throughout the life cycle of buildings. In other words, resources should be utilized efficiently, not only in new buildings but also in commercial, residential, and public

buildings undergoing large renovations. According to the report, since one-third of the total waste generated in the EU is construction and demolition waste (C&DW), the European Commission introduced a strategy, the Construction 2020 Action Plan, with the key objective of improving resource efficiency, environmental performance, and business opportunities. The strategy focuses on energy and resource efficiency to strengthen sustainable competitiveness in the construction sector and related companies. The specific policy measures of the Construction 2020 Action Plan are the Cohesion Policy and Horizon 2020, which include policies incentivizing energy and resource efficiency and supporting public green space procurement guidelines. Resource efficiency in the construction sector is mainly evaluated in terms of the environmental impact of inputs and outputs during raw material production, construction, utilization, maintenance, demolition, and disposal activities. The state of resource efficiency in the construction sector is analyzed through available data indicators provided by the companies responsible for the direct generation and disposal of construction wastes. According to the 2014 statistics on waste generation in the EU, 38% was generated in the construction sector, as shown in Figure 1 [26,27]. According to the 2015 waste generation and disposal statistics published by the Ministry of Environment and the Korea Environment Corporation, construction waste accounted for the largest portion (48.9%) of total waste in South Korea, as shown in Figure 2 [19,28].

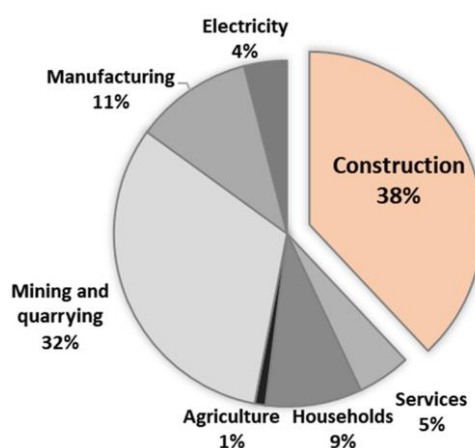


Figure 1. EU-28 waste generation.

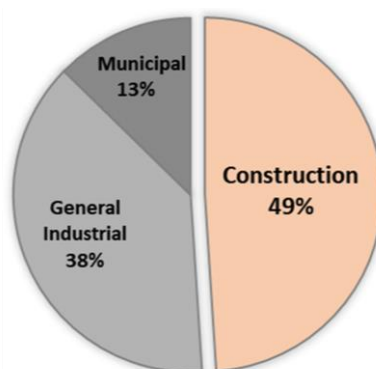


Figure 2. South Korea waste generation.

In Figure 3, the average amount of construction waste decreased by 10.7% from 2010 to 2014 in the EU. The amount of waste discarded per capita since 2014 reflects the population size and activity level in the construction sector. The amount of waste generated has declined in half of the member countries, and especially in Spain, with a significant drop of 59.3% between 2010 and 2014 [26,27]. However, as shown in Figure 4, the amount of construction waste in South Korea has steadily increased compared to domestic and general waste from commercial businesses. Additionally, construction

waste generation in the country is expected to increase further since the reconstruction period has recently been shortened from 40 to 30 years for row houses and apartment buildings [19,28].

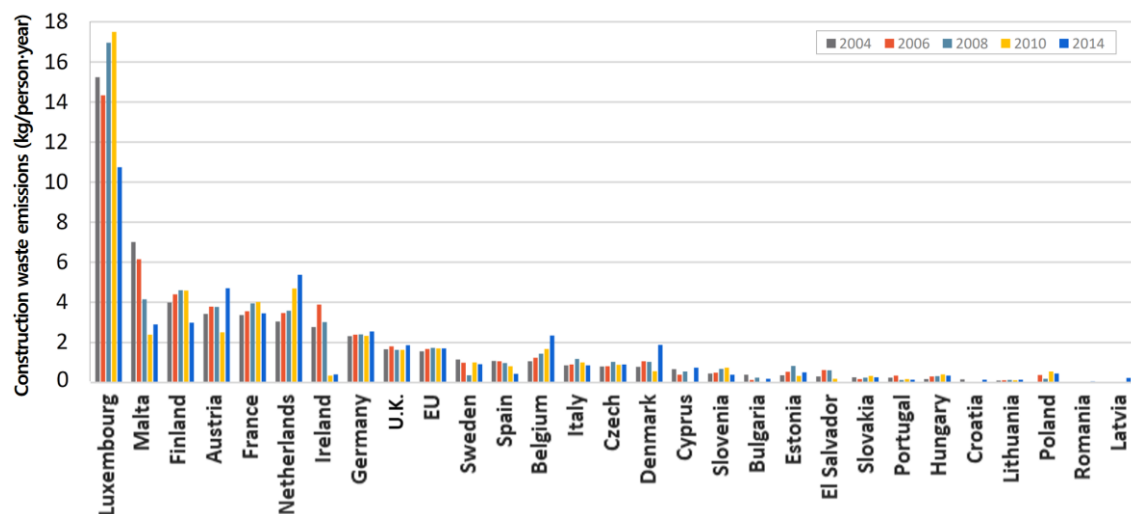


Figure 3. Generation of waste by the construction sector in the EU-28 in 2004, 2006, 2008, 2010 and 2014.

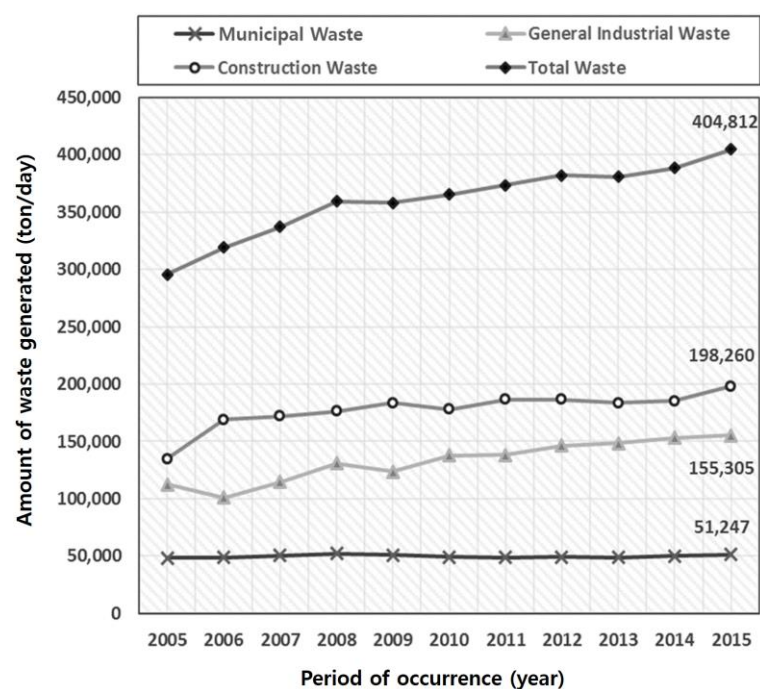


Figure 4. Current status of South Korea's waste generation.

Construction wastes were classified as shown in Table 1. The amount of construction waste generated from 2010 to 2015 indicates that concrete and mixed waste are the dominant types. As shown by the loss rates of building materials, waste generation in various types and amounts is unavoidable at construction sites. Regarding the disposal and management processes for wastes generated in the construction phase, collection and transport companies take the waste from site storage yards and primarily separate them by type at their sites. Intermediary disposal companies, such as specialized disposal companies and local logistics centers, are contracted to handle recyclable wastes that are mostly simple, low-value roadbed materials [29]. Subsequently, the construction wastes are recycled as secondary concrete products, and those that cannot be recycled are taken to the final disposal site to be incinerated and buried in landfills. Although the waste generated in the construction phase is more

diverse and distinctive in terms of the material characteristics compared to the waste generated in the demolition phase, it is not completely reclassified and is landfilled or incinerated [30,31].

Table 1. Classification and occurrence of construction waste (unit: ton/day).

Waste Classification		2010	2011	2012	2013	2014	2015
Construction waste materials	Concrete	114,302	121,181	117,754	111,653	114,908	124,451
	Asphalt concrete	32,535	35,245	35,738	35,398	33,725	35,509
	Others ¹	2132	2339	2957	3280	2393	3230
	Sub total	148,969	158,765	156,448	150,331	151,026	163,190
Combustibility wastes	Wood	636	592	683	704	866	923
	Synthetic resin	839	1096	1261	1695	1586	1654
	Others ²	98	20	21	19	67	11
	Sub total	1573	1708	1964	2418	2519	2588
Non-combustibility wastes	Construction sludge	645	1403	644	1052	707	995
	Others ³	9	4	7	6	170	41
	Sub total	654	1407	651	1058	877	1036
Construction soil debris		5347	4838	5094	5067	5863	7659
Mixed construction wastes ⁴		21,577	19,699	22,471	24,664	25,097	23,787
Total		178,120	186,417	186,629	183,538	185,382	198,260

¹ Construction waste materials: waste brick, waste block, and waste roofing tile. ² Combustible wastes: waste fiber and waste wallpaper. ³ Non-combustible wastes: waste metal, waste glass, waste tile, and waste ceramics.

⁴ Mixed construction wastes: mixed construction waste, waste board, and waste panel.

The narrow range of waste classification is not suitable for encouraging its separation and reduction. Currently, combustible and non-flammable wastes are mixed, stored in arm-roll boxes, collected, and transported to collection yards to be buried without specific separation [32,33]. Identifying the key waste generated during the construction phase will contribute to establishing an eco-friendly construction production system that can minimize construction waste and maximize recycling rates.

3. Materials

In this study, the amount of waste generated at a construction site was estimated by obtaining the bill of quantities from an actual multi-family housing building to determine the major construction wastes using a life cycle assessment. Multi-family housing buildings, which account for the largest portion of the permit area used in South Korea, were selected as the subject for the case study analysis, and the result was used to determine the major wastes. As shown in Table 2, a high-rise capital apartment complex project with 643 household units, completed by a construction company known for excellent site management skills, was the site selected for the case study.

Table 2. Overview of a high-rise capital apartment complex project.

Classification	Contents
Project title	S International multi-purpose complex
Structural type	Reinforced concrete
Principal use	Apartment buildings
Site area	40,548.50 m ²
Building area	5737.4747 m ²
Gross floor area	125,120.1410 m ²
Floor area ratio	14.14%
Floor space index	219.67%
Number of households	643 households

4. Methods

4.1. Analysis of the Construction Waste Quantities

The amount of waste generated at the construction site was estimated based on the quantities bill of the project and by converting the various units of the materials using the weight conversion factors and loss rates. The quantity, specification, weight, and product name of each material were confirmed through the quantities bill, and the materials were arranged by weight based on the unit weight conversion, as shown in Table 3. Thousands of materials and processes are used to complete a single building, and it is inefficient to analyze all possible materials and processes. Many of them are used for large multi-family housing buildings, such as the subject of this analysis.

Table 3. Conversion factors of the main construction materials.

Construction Materials	Specification	Unit	Conversion Factor (ton/unit)	Source
Concrete	Reinforced concrete	m ³	2.40	A
	Plain concrete	m ³	2.30	A
	Mortar	m ³	2.10	A
Cement	Cement	m ³	3.15	A
Insulation	Expanded polystyrene first	m ³	0.030	B
	Expanded polystyrene second	m ³	0.025	B
	Expanded polystyrene third	m ³	0.020	B
	Glass wool (24k)	m ³	0.024	B
	Glass wool (48k)	m ³	0.048	B
	Extruded polystyrene first	m ³	0.030	B
	Extruded polystyrene second	m ³	0.025	B
	Extruded polystyrene third	m ³	0.020	B
	Phenolic foam	m ³	0.030	B
Board	Gypsum board	m ³	0.60	B
Glass	Glass	m ³	2.55	B

A: Standard of the estimate for the construction works conversion factor. B: Passive House Institute Korea conversion factor.

In this study, the cutoff criteria provided in ISO 21930 were used to conduct the life cycle assessment of the construction waste. The cutoff criteria specify the unit processes, quantities, energy consumption, environmental significance, etc., to be excluded in a study. ISO 21930 recommends that a life cycle assessment includes materials that contribute at least 95% of the mass or environmental relevance among all the materials that constitute the subject of the assessment. Hence, in this study, the amount of construction waste generated was analyzed for the materials accounting for 95% of the cumulative weight contribution. The standard of estimation from the Korea Construction Management Corporation and data from the Passive House Institute Korea were used as the basis for the unit weight, and in the case of manufactured products, units were converted based on the weight of each product [33].

4.2. Life Cycle Assessment

A life cycle assessment is an environmental evaluation technique that quantifies the amount of input resources and pollutant emissions generated throughout the entire process of raw material production, manufacture, usage, and disposal of a product. In addition to a risk assessment, the International Organization of Standardization established the technical specifications for a life cycle assessment under the ISO 14000 environmental management family. In this study, the assessment was conducted based on the ISO 14040 series (life cycle assessments) and ISO 21930 (environmental declaration of building products). The major waste materials were determined by evaluating the six types of environmental

impacts that could not be analyzed through simple quantification: GWP, ADP, AP, EP, ODP, and POCP. The impact quantification factor (characterization factor) of each category was calculated, and the potential contribution to the environmental load was obtained by multiplying the loads (emission or release) of the inventory data classified into each impact category by the characterization factor (Equation (1)):

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

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 the 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 reference materials and impact index for each environmental impact category were applied based on the environmental product declaration labeling database, the national life cycle inventory database (LCI DB; Ministry of Trade, Industry, and Energy and Ministry of Environment), and the National Environmental Information DB (Ministry of Land, Transport and Maritime Affairs), as shown in Table 4 [33–38].

Table 4. Selection of the life cycle inventory databases (LCI DBs) for the construction materials (partial).

Classification	LCI DB Title	Source Data
Concrete	Ready-mixed concrete 25-240-15	National LCI DB
Rebar	Electric steel deformed bars	National LCI DB
Sand	Sand	National environmental database
Insulation	Glass wool	National LCI DB
Cement	Cement	National LCI DB
Gypsum board	Gypsum board	National LCI DB
Polystyrene panel	Foaming polystyrene board	National environmental database

Global warming is the rise in the average temperature of the Earth's surface. Its major cause is the emission of greenhouse gases, including CO₂. The reference substance for global warming is CO₂, and there are 23 impact substances, including CH₄, N₂O, HFCs, and SF₆. In this study, the global warming potential was calculated using CO₂ as the reference substance and applying the GWP provided by the International Panel on Climate Change (IPCC) to the environmental loads of the impact substances [39]. Ozone depletion is the reduction in density of the ozone layer in the stratosphere, which is 15 to 30 km above the ground. This is mainly caused by CFCs and causes skin cancer because of the increase in ultraviolet rays reaching the Earth's surface. The reference substance for ozone depletion is trichlorofluoromethane (CFC-11), and there are 22 impact substances, including bromotrifluoromethane (Halon 1301), hydrobromofluorocarbons, hydrochlorofluorocarbons, methyl bromide, and methyl chloride. The ozone layer impact was calculated using CFC-11 as the reference substance and applying the ODP provided by the World Meteorological Organization (WMO) to the environmental loads of the impact substances [40,41]. Acidification is the increase in the acidity of rivers, streams, and soil due to atmospheric pollutants, such as SO₂, NH₃, and NO_x. It increases the elution of heavy metals and affects ecosystems, such as the nutrient and feed supplies of fish, plants, and animals. The reference substance of acidification is SO₂, and there are 23 impact substances, including NH₃, H₂SO₄, and NO_x. The acidification was calculated using SO₂ as the reference substance and applying the AP provided by Heijung et al. and Hauschild and Wenzel to the environmental loads of the impact substances [42,43]. Abiotic depletion is the environmental impact caused by the use of resources. The reference substance is Sb, and there are more than 90 impact substances, including Al, Cd, Fe, Au, Hg, natural gas, and crude oil. The abiotic depletion was calculated using Sb as the reference substance and applying the ADP provided by Guinee et al. to the environmental loads of the impact substances [44]. Photochemical oxidant creation refers to the reaction between air pollutants and sunlight, which creates chemical compounds, such as ozone. Such chemical compounds adversely

affect ecosystems, including human health and crop growth. The reference substance of photochemical oxidant creation is ethylene, and there are more than 100 impact substances, including acetone, benzene, CO, ethane, methane, and toluene. The photochemical oxidant creation was calculated using ethylene as the reference substance and applying the POCP provided by Jenkin and Hayman and Derwent et al. to the environmental loads of the impact substances [45,46]. The eutrophication is the rapid multiplication of algae due to an oversupply of nutrients in the aquatic ecosystem from chemical fertilizers and sewage, causing red tides. The reference substance of eutrophication is PO_4^{3-} , and there are 11 impact substances, including NH_3 , NH_4 , N_2 , NO_2 , and P. The eutrophication was calculated using PO_4^{3-} as the reference substance and applying the EP provided by Heijung et al. to the environmental loads of the impact substances [42].

5. Results

5.1. Analysis of the Major Wastes in the Construction Phase

The results of the multi-family housing complex construction site waste analysis showed that 167 types of waste materials were generated, 41 of which accounted for 95% of the cumulative weight contribution. The quantity, weight conversion factors, and loss rates for the top 20 waste materials are listed in Table 5. Materials not included in Table 5 include plywood gypsum boards for woodwork, steel trowel finish for plasterwork, and specific stones for masonry work.

Table 5. Amounts of the construction wastes based on weight.

No.	Work Type	Construction Materials	Specification	Unit	Quantity (Unit)	Classification of Waste	Conversion Factor	Material Loss Rate	Construction Waste (kg)
1	Reinforced concrete work	Concrete	20-240-15	m ³	91,563	Concrete	2300.00	0.003	631,784.7
2	Masonry work	Cement brick	190*90*57	EA	4,593,749	Concrete block	2.00	0.030	275,624.9
3	Reinforced concrete work	Rebar	H10-H13	ton	7518	Rebar	1000.00	0.030	225,540.0
4	Plaster work	Cement	Bulk	ton	4178	Concrete	1000.00	0.030	125,340.0
5	Reinforced concrete work	Concrete pad	25-180-12	m ³	9947	Concrete	2300.00	0.003	68,634.3
6	Water-proofing work	Ordinary Portland cement	40 kg	bag	35,795	Cement	40.00	0.030	42,954.0
7	Water-proofing work	Sand	-	m ³	2214	Sand	1700.00	0.010	37,638.0
8	Plaster work	Cement	Bubble, Bulk	ton	1243	Concrete	1000.00	0.030	37,290.0
9	Masonry work	Sand	-	m ³	2145	Sand	1700.00	0.010	36,465.0
10	Plaster work	Sand	-	m ³	2091	Sand	1700.00	0.010	35,547.0
11	Plaster work	Ordinary Portland cement	40 kg	bag	29,451	Cement	40.00	0.030	35,341.2
12	Carpentry	Gypsum board	9.5 T	m ²	67,694	Gypsum board	6.18	0.080	33,440.8
13	Tile work	Sand	-	m ³	1743	Sand	1700.00	0.010	31,331.0
14	Masonry work	Cement brick	6'	EA	74,141	Concrete block	14.00	0.030	31,139.2
15	Reinforced concrete work	Gypsum board	-	m ²	190,231	Gypsum board	7.60	0.020	28,915.1
16	Tile work	Ordinary Portland cement	40 kg	bag	21,368	Cement	40.00	0.030	25,641.6
17	Plaster work	Mortar	T18	m ²	42,835	Concrete block	18.00	0.030	23,130.9
18	Finishing work	Gypsum board	15 T	m ²	24,047	Gypsum board	9.75	0.080	18,756.7
19	Tile work	Earthenware	-	m ²	36,917	Tile	14.40	0.030	15,948.1
20	Tile work	Earthenware	-	m ²	26,742	Tile	18.00	0.030	14,548.7

To easily conduct an environmental impact assessment through characterization, 41 materials were grouped into nine categories: concrete, concrete blocks, rebar, sand, general cement, gypsum board, tile, insulation, and stone. As shown in Table 6, the total weight of the construction waste generated was 1,951,939 kg, where concrete accounted for 883,437 kg, or 45%. Despite having a low

loss rate of 0.003%, concrete accounted for the largest portion of waste because, according to the bill of quantities, it is a major input material. The most common construction wastes after concrete were concrete block, rebar, sand, general cement, and gypsum boards. Insulation and granite materials accounted for the smallest amounts at 1.53% and 0.70%, respectively.

Table 6. Results of construction waste amounts.

Classification of Waste	Construction Waste Amount	Share
Concrete	883,437 kg	45.26%
Concrete block	331,354 kg	16.98%
Rebar	225,540 kg	11.55%
Sand	147,416 kg	7.55%
Cement	126,520 kg	6.48%
Gypsum board	125,174 kg	6.41%
Tile	68,968 kg	3.53%
Insulation	29,886 kg	1.53%
Granite	13,645 kg	0.70%
Total	1,951,940 kg	100.00%

Since over 95% of concrete and cement products are recycled in South Korea, albeit in the form of simple roadbed materials, and rebar is fully recycled, the remaining gypsum boards are a major waste that needs to be managed. In Japan, where the recycling rate of construction waste is outstanding, gypsum board manufacturers have implemented a broad-range recycling strategy with a zero-waste goal. Gypsum boards used in new buildings generate approximately 420,000 tons of waste, or 10% of the total annually. Approximately 110,000 tons of gypsum board waste is reused in the manufacturing process through active management and the Japanese broad-range recycling strategy, whereby a manufacturer can recover and recycle its product when it becomes an industrial waste by transporting it back to its sales branch without requiring a separate business permit for waste disposal.

5.2. Analysis of Major Construction Wastes Using the Life Cycle Assessment

The waste materials derived with loss rates were analyzed using a life cycle assessment. The environmental impact characterization index was calculated based on the production stage of the material and was adopted from a study arguing that materials discarded as waste can be considered as unnecessary production. In this study, as shown in Table 7, the major construction wastes were identified via the life cycle assessment by using a characterization technique that evaluated the six types of environmental impacts: GWP, ADP, AP, EP, ODP, and POCP. Using the cutoff criteria, the 41 material types were grouped into nine environmental impact characterization index items: concrete, concrete block, general cement, rebar, tile, gypsum board, insulation, sand, and granite. Each category was analyzed for the environmental impact characterization value under the six environmental impact categories. Cement bricks and cement blocks used for plastering, waterproofing, and masonry were grouped into the concrete block category. The environmental impact characterization index for a life cycle assessment of cement bricks was also used for cement blocks, while that of mortar was derived based on the mixing ratio of cement and sand. The material units that had been converted to determine the construction waste quantity were reconverted based on the characterized life cycle assessment units.

Figure 5 shows the contribution of each construction waste by environmental impact. The analysis indicated that the construction wastes with a significant impact on global warming were concrete blocks, concrete, cement, and rebar, with a contribution level of 95% or higher. The waste accounting for 95% of the contribution level in other categories was: insulation material at 51%, rebar at 18%, concrete block at 12%, and concrete at 10% for resource depletion; concrete block at 28%, rebar at 27%, insulation materials at 22%, general cement at 9%, and concrete at 5% for acidification; and concrete

block at 31%, rebar at 28%, stone material at 15%, insulation material at 10%, and general cement at 8% for eutrophication.

Table 7. Amount of the construction wastes for each environmental impact.

Classification of Waste					Work Type	Unit	Waste Amount (Unit)	Environmental Impact Assessment Result Value					
								GWP	ADP	AP	EP	ODP	POCP
								kg-CO _{2eq}	kg-Sb	kg-SO _{2eq}	kg-PO ₄ ³⁻ eq	kg-CFC-11eq	kg-C ₂ H _{4eq}
Concrete block	Cement mortar	Plaster	ton	23.1	6.2 × 10 ⁴	1.4 × 10 ²	1.6 × 10 ²	2.8 × 10 ¹	3.2 × 10 ⁻³	6.9 × 10 ¹			
	Steel trowel finish	Masonry Plaster	ton	17.3	4.7 × 10 ⁴	1.0 × 10 ²	1.2 × 10 ²	2.1 × 10 ¹	2.4 × 10 ⁻³	5.2 × 10 ¹			
			ton	14.8	4.0 × 10 ⁴	8.6 × 10 ¹	1.1 × 10 ²	1.8 × 10 ¹	2.0 × 10 ⁻³	4.4 × 10 ¹			
	Protection mortar	Plaster	ton	14.3	3.9 × 10 ⁴	8.3 × 10 ¹	1.0 × 10 ²	1.7 × 10 ¹	2.0 × 10 ⁻³	4.3 × 10 ¹			
	Cement brick	Masonry	ton	261.9	3.2 × 10 ⁴	3.9 × 10 ¹	4.1 × 10 ¹	5.9 × 10 ⁰	1.3 × 10 ⁻³	3.4 × 10 ⁰			
	Dry cement mortar	Masonry	m ³	54.9	8.4 × 10 ¹	1.3 × 10 ⁻¹	1.8 × 10 ⁻¹	2.7 × 10 ⁻²	3.2 × 10 ⁻⁶	1.5 × 10 ⁻¹			
		Plaster	m ³	16.3	2.5 × 10 ¹	4.0 × 10 ⁻²	5.3 × 10 ⁻²	8.0 × 10 ⁻³	9.4 × 10 ⁻⁷	4.5 × 10 ⁻²			
Rebar	Rebar	Reinforced concrete	ton	225.5	7.9 × 10 ⁴	6.3 × 10 ²	5.2 × 10 ²	7.8 × 10 ¹	2.4 × 10 ⁻³	7.7 × 10 ¹			
Cement	Cement bulk	Water proofing	ton	43.0	4.5 × 10 ⁴	4.9 × 10 ¹	5.6 × 10 ¹	8.0 × 10 ⁰	1.5 × 10 ⁻³	1.3 × 10 ¹			
		Plaster	ton	35.3	3.7 × 10 ⁴	4.0 × 10 ¹	4.6 × 10 ¹	6.6 × 10 ⁰	1.3 × 10 ⁻³	1.1 × 10 ¹			
	Cement-40kg	Tile	ton	22.6	2.4 × 10 ⁴	2.6 × 10 ¹	2.9 × 10 ¹	4.2 × 10 ⁰	8.0 × 10 ⁻⁴	6.8 × 10 ⁰			
		Masonry	ton	25.6	2.7 × 10 ⁴	2.9 × 10 ¹	3.3 × 10 ¹	4.8 × 10 ⁰	9.1 × 10 ⁻⁴	7.8 × 10 ⁰			
Concrete	18 MPa	Reinforced concrete	m ³	29.8	1.3 × 10 ⁴	4.7 × 10 ¹	2.1 × 10 ¹	2.4 × 10 ⁰	1.4 × 10 ⁻³	3.4 × 10 ¹			
	16 MPa	Reinforced concrete	m ³	8.5	3.6 × 10 ³	1.3 × 10 ¹	5.9 × 10 ⁰	6.9 × 10 ⁻¹	3.9 × 10 ⁻⁴	9.6 × 10 ⁰			
	24 MPa	Reinforced concrete	m ³	274.7	1.2 × 10 ⁵	3.0 × 10 ²	7.4 × 10 ¹	2.5 × 10 ⁻¹	1.3 × 10 ⁻²	3.2 × 10 ²			
Board	Gypsum board-9.5T	Interior finishing	ton	29.6	4.1 × 10 ³	1.1 × 10 ¹	2.3 × 10 ¹	3.9 × 10 ⁰	4.2 × 10 ⁻⁴	5.6 × 10 ⁰			
	Plywood board	Interior finishing	ton	7.3	1.0 × 10 ³	2.8 × 10 ⁰	5.7 × 10 ⁰	9.6 × 10 ⁻¹	1.0 × 10 ⁻⁴	1.4 × 10 ⁰			
	Gypsum board-9.5T	Carpentry	ton	17.8	2.5 × 10 ³	6.9 × 10 ⁰	1.4 × 10 ¹	2.4 × 10 ⁰	2.5 × 10 ⁻⁴	3.4 × 10 ⁰			
	Gypsum board-15T	Carpentry	ton	11.6	1.6 × 10 ³	4.5 × 10 ⁰	9.1 × 10 ⁰	1.5 × 10 ⁰	1.6 × 10 ⁻⁴	2.2 × 10 ⁰			
	Plywood board	Carpentry	ton	2.9	4.0 × 10 ²	1.1 × 10 ⁰	2.3 × 10 ⁰	3.9 × 10 ⁻¹	4.1 × 10 ⁻⁵	5.6 × 10 ⁻¹			
	Sound-proofing	Carpentry	ton	16.6	2.3 × 10 ³	6.4 × 10 ⁰	1.3 × 10 ¹	2.2 × 10 ⁰	2.4 × 10 ⁻⁴	3.2 × 10 ⁰			
Insulation	T75	Carpentry	ton	6.5	1.4 × 10 ⁴	1.1 × 10 ³	2.7 × 10 ²	1.8 × 10 ¹	1.9 × 10 ⁻⁴	4.2 × 10 ¹			
	T105	Carpentry	ton	3.8	7.9 × 10 ³	6.7 × 10 ²	1.6 × 10 ²	1.1 × 10 ¹	1.1 × 10 ⁻⁴	2.5 × 10 ¹			
Sand	Sand	Water proofing	m ³	20.9	8.1 × 10 ¹	1.9 × 10 ⁻¹	2.3 × 10 ⁻¹	4.0 × 10 ⁻²	4.6 × 10 ⁻⁶	6.8 × 10 ⁻²			
		Plaster	m ³	22.1	8.6 × 10 ¹	2.0 × 10 ⁻¹	2.4 × 10 ⁻¹	4.3 × 10 ⁻²	4.9 × 10 ⁻⁶	7.2 × 10 ⁻²			
		Tile	m ³	21.5	8.3 × 10 ¹	2.0 × 10 ⁻¹	2.4 × 10 ⁻¹	4.1 × 10 ⁻²	4.7 × 10 ⁻⁶	6.9 × 10 ⁻²			
		Masonry	m ³	18.4	7.1 × 10 ¹	1.7 × 10 ⁻¹	2.0 × 10 ⁻¹	3.5 × 10 ⁻²	4.1 × 10 ⁻⁶	6.0 × 10 ⁻²			
Tile	Ceramic tile	Tile	ton	39.9	1.4 × 10 ⁴	7.7 × 10 ¹	3.4 × 10 ¹	4.9 × 10 ⁰	1.3 × 10 ⁻⁴	2.5 × 10 ¹			
	Porcelain tile	Tile	ton	29.1	1.0 × 10 ⁴	5.6 × 10 ¹	2.5 × 10 ¹	3.6 × 10 ⁰	9.5 × 10 ⁻⁵	1.8 × 10 ¹			
Granite	Granite	Masonry	m ³	5.9	4.9 × 10 ³	1.4 × 10 ¹	3.0 × 10 ¹	4.3 × 10 ¹	1.6 × 10 ⁻⁴	2.2 × 10 ⁰			

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

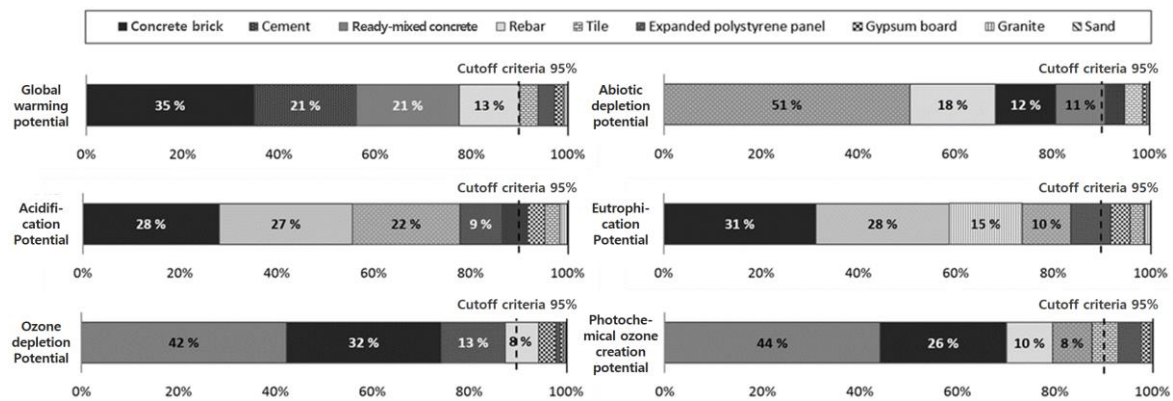


Figure 5. Contribution of the construction wastes on each environmental impact.

Meanwhile, regarding ozone depletion, concrete contributed 42%, concrete block 32%, general cement 13%, and rebar 7%. Regarding photochemical ozone creation, concrete, concrete block, rebar, insulation material, and general cement constituted 93%. The results of the environmental impact characterization assessment revealed that concrete, concrete block, and cement waste accounted for over 70% of the contribution level in all of the environmental impact categories except resource depletion. Table 8 shows the details of the environmental impact assessment of the construction waste. The shaded cells indicate the materials accounting for the top 95% cumulative contribution for each environmental impact category. Based on the contribution level analysis, the five major construction wastes selected were concrete, rebar, cement, gypsum board, insulation material, and concrete block, which collectively satisfied the cutoff criteria of 95%.

Table 8. Environmental impact assessment of construction wastes per gross floor area.

Construction Waste	GWP		ADP		AP		EP		ODP		POCP	
	Emission	Share	Emission	Share	Emission	Share	Emission	Share	Emission	Share	Emission	Share
	kg-CO _{2eq}	%	kg-Sb _{eq}	%	kg-SO _{2eq}	%	kg-PO ₄ ³⁻ _{eq}	%	kg-CFC-11 _{eq}	%	kg-C ₂ H _{4eq}	%
Concrete	1.34 × 10 ⁵	21.27	3.61 × 10 ²	10.12	1.00 × 10 ²	5.27	3.35 × 10 ⁰	1.17	1.44 × 10 ⁻²	42.28	3.60 × 10 ²	44.18
Concrete block	2.20 × 10 ⁵	34.92	4.44 × 10 ²	12.44	5.35 × 10 ²	28.20	8.97 × 10 ¹	31.32	1.09 × 10 ⁻²	32.00	2.11 × 10 ²	25.90
Cement	1.34 × 10 ⁵	21.27	1.43 × 10 ²	4.01	1.65 × 10 ²	8.70	2.35 × 10 ¹	8.21	4.49 × 10 ⁻³	13.18	3.83 × 10 ¹	4.70
Rebar	7.94 × 10 ⁴	12.60	6.29 × 10 ²	17.63	5.21 × 10 ²	27.46	7.84 × 10 ¹	27.38	2.35 × 10 ⁻³	6.90	7.70 × 10 ¹	9.45
Insulation	2.14 × 10 ⁴	3.40	1.81 × 10 ³	50.73	4.20 × 10 ²	22.14	2.86 × 10 ¹	9.99	3.00 × 10 ⁻⁴	0.88	6.63 × 10 ¹	8.14
Tile	2.43 × 10 ⁴	3.86	1.33 × 10 ²	3.73	5.83 × 10 ¹	3.07	8.48 × 10 ⁰	2.96	2.24 × 10 ⁻⁴	0.66	4.34 × 10 ¹	5.33
Gypsum board	1.18 × 10 ⁴	1.87	3.32 × 10 ¹	0.93	6.71 × 10 ¹	3.54	1.13 × 10 ¹	3.95	1.22 × 10 ⁻³	3.58	1.63 × 10 ¹	2.00
Granite	4.85 × 10 ³	0.77	1.41 × 10 ¹	0.40	2.98 × 10 ¹	1.57	4.29 × 10 ¹	14.98	1.56 × 10 ⁻⁴	0.46	2.22 × 10 ⁰	0.27
Sand	3.21 × 10 ²	0.05	7.66 × 10 ⁻¹	0.02	9.11 × 10 ⁻¹	0.05	1.59 × 10 ⁻¹	0.06	1.82 × 10 ⁻⁵	0.05	2.68 × 10 ⁻¹	0.03

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

Stone materials were found to be a major construction waste for the eutrophication category but were ultimately excluded because their contribution level, 0.5%, was minimal in all other environmental impact categories. Gypsum boards were one of the most discarded materials in terms of weight, but they were found to provide a minimal contribution, namely, under 5% in all six environmental impact assessment categories. In contrast, insulation materials were selected as a major waste based on the high contribution level of 51% in the resource depletion category, as well as relatively high levels in the acidification, eutrophication, and photochemical ozone creation categories, despite accounting for only 1% or 29,886 kg of the total construction waste generated.

6. Conclusions

In the construction phase, despite the various high-quality construction waste that can be recycled being generated because of the application of the loss rates, the current wastes are not completely reclassified and are being landfilled or incinerated. Selective waste management during the construction

phase will not only contribute to the establishment of an eco-friendly construction production system that minimizes waste and maximizes recycling rates but will also provide economic benefits.

In this study, the major construction wastes from an environmental impact perspective were identified through a life cycle assessment. The quantities of the 167 types of construction waste were estimated for a multi-family housing construction site using material loss rates and weight conversion factors. An environmental impact assessment was conducted in six categories on the construction waste constituting 95% of the cumulative weight contribution, or 41 types of waste, and the following conclusions were made:

1. Based on the contribution level analysis results, and the cutoff criteria of 95%, five types of major construction wastes were determined: concrete, rebar, cement, insulation material, and concrete blocks.
2. As a key management target in the construction phase, concrete was the most discarded material in terms of weight and demonstrated the highest contribution levels of 42% and 44% in ozone depletion and photochemical ozone creation, respectively, while contributing little to acidification and eutrophication.
3. Gypsum boards were found to be heavily discarded in terms of the waste amount as a weight, but the environmental impact assessment results indicated the lowest contribution level of less than 5% in all six categories.
4. In contrast to gypsum boards, insulation materials accounted for 1% of the total waste generated but were identified by the environmental impact assessment to have the highest contribution level in resource depletion (51%) and relatively high levels of acidification, eutrophication, and photochemical ozone creation.
5. The results from the environmental impact characterization assessment indicated that concrete, concrete block, and cement waste accounted for over 70% of the contribution level in all the environmental impact categories except resource depletion.

In this study, apartment buildings made using reinforced concrete, which account for the largest portion of the permit area used in South Korea, were selected as the subjects for the analysis, and the result was used to determine the major wastes. As a follow-up study, we plan to examine the derived major construction waste, which will be further subdivided through the analysis of construction waste according to buildings of various uses and structure types. This is believed to contribute to the use of government policies to reinforce the obligation to select construction waste targets to be suppressed and separately discharged at construction sites.

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