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Experimental Investigation of Carbon and Cost Reductions Using Waste Glass-based Low-carbon Permeable Boundary Blocks – A Case Study in South Korea

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In this study, the possibility of utilizing waste glass sand (GS) as a sustainable alternative to natural sand (NS) for the production of low-carbon permeable boundary blocks (PBs) was investigated. A modular life cycle assessment approach was employed to evaluate both the environmental and economic impacts of using GS in PBs. The results indicated that substituting landfill-designated waste glass with GS can replace approximately 28396 tons of NS annually in South Korea, thereby significantly reducing resource depletion and landfill demand. PBs incorporating GS achieved up to a 68% reduction in carbon emissions compared with traditional blocks. However, the life-cycle cost analysis showed that the substitution of NS with GS resulted in only 4% cost savings for manufacturers when waste glass disposal costs were excluded. These findings suggest that although GS offers clear environmental advantages, additional tangible economic incentives may be required to encourage its widespread utilization by manufacturers.

1. Introduction

1.1 Background and context

Concrete is one of the most widely used materials in the construction of buildings and civil infrastructure such as bridges and roads.(1,2) In South Korea, approximately 43.2 million tons of clinker have been produced annually over the past five years to meet the demand for concrete. Clinker production results in the emission of approximately 39 million tons of greenhouse gases (GHGs) each year, accounting for more than 5% of the country's total annual GHG emissions.(3) These emissions significantly contribute to global climate change. Accordingly, various strategies, including the use of supplementary cementitious materials (SCMs), have been implemented to reduce GHG emissions during concrete production.

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In addition to reducing cement consumption, sustainable construction practices such as resource conservation and waste minimization are essential for decarbonizing the construction industry.[4] Aggregates used in concrete, such as sand, gravel, and crushed stone, contribute significantly to its total weight, highlighting the need for proper management to preserve natural resources. Since 2008, South Korea has mandated the use of recycled aggregates (RAs) by law to reduce construction waste and preserve natural aggregate sources. To ensure the quality of the RAs, the aged mortar must be removed from the surface. Although coarse RAs are actively recycled because of their relatively large particle sizes, fine RAs require additional procedures and costs to eliminate residual mortar and impurities, making them less favorable for reuse.[5] As a result, natural sand (NS) has remained the preferred option in the Korean construction industry, leading to the extraction of NS from rivers and marine environments and raising increasing environmental concerns.[6]

Waste glass is a major obstacle to effective waste management and minimization. Globally, only approximately 21% of the 130 million tons of glass produced annually is recycled. The unrecycled portion is typically stockpiled or landfilled, and because of the non-biodegradable nature of glass, it contributes significantly to environmental pollution.[4] To address this issue, various industries are exploring recycling strategies, and in the construction sector, waste glass has been investigated for use as SCMs in powdered form or as a substitute for NS after crushing. Waste glass sand (GS) has attracted attention as a promising alternative to NS because it can simultaneously mitigate environmental pollution and enhance resource sustainability.

Various studies have been conducted on the use of GS in concrete; however, two major limitations have been identified. First, when the GS content exceeds 50%, the mechanical properties of the concrete tend to deteriorate owing to the smooth surface, angular shape, and high aspect ratio of the GS particles.[7] Second, the high alkalinity of concrete promotes the dissolution of amorphous silica in GS, accelerating the alkali-silica reaction (ASR).[8] Although the direct application of GS in structural concrete is limited, it has shown considerable potential as a construction material for products such as concrete, masonry, and paving blocks.[9] In particular, Yang *et al.* reported that the long-term monitoring of dry-mixed concrete blocks containing GS revealed no durability degradation caused by ASR.[10] Furthermore, as glass inherently reduces water absorption, the use of GS in permeable blocks is expected to generate synergistic benefits.

Although numerous studies have recommended the use of GS as part of sustainable construction practices, further investigation is required to assess the environmental impacts associated with the production and application of GS over their life cycle. Some studies have reported that recycling waste glass into GS may result in higher energy consumption and carbon emissions than landfill.[11] In response, several studies in countries such as Australia and China have evaluated the environmental impacts of GS production and found that the condition of waste glass (i.e., whether washing and impurity removal are required) significantly affects its environmental performance.[12,13] Therefore, to promote the recycling of waste glass into GS, it is essential to understand the current management status of waste glass in each country and quantify the environmental impacts of the GS production processes. In this context, this study is one of the earliest attempts to evaluate the environmental and economic impacts of recycling waste glass for GS in South Korea.

In this study, the current status of waste glass management in South Korea was investigated and environmental and economic analyses of its recycling into GS were conducted. First, a material and energy inventory, including raw material inputs and energy consumption, was established on the basis of field data collected from a GS production facility. Subsequently, a life cycle assessment (LCA) was performed to evaluate the material and energy flows involved in the production of both traditional and permeable boundary blocks. Finally, the potential economic benefits and carbon emission reductions associated with the use of GS in permeable boundary blocks were quantitatively assessed.

1.2 Status of waste glass management in South Korea

In South Korea, waste glass is classified into three categories: discharged municipal waste, mixed municipal waste, and construction waste. Among these, municipal waste discharged separately is collected by local governments or private collectors and transported to sorting facilities. It was initially classified into three types: reusable glass bottles, non-reusable but recyclable waste glass, and non-recyclable waste glass. Reusable bottles are sent to recycling companies, whereas the remaining non-reusable or non-recyclable waste glass is transported along with mixed municipal and construction waste to intermediate processing companies (IPCs). IPCs conduct further sorting to categorize waste into three types: recyclable glass, non-recyclable glass, and glass containing excessive impurities that make separation infeasible. These subcategories were subsequently directed toward appropriate processes for recycling, landfilling, and incineration. All waste glass processing data are reported to the government through the national system (Allbaro). The government compiles these records and publishes the aggregated statistics using the National Database Portal (KOSIS).[14]

Figure 1 shows the trends in waste glass generation and treatment in South Korea from 2019 to 2023. Approximately 0.53 million tons of waste glass are generated annually, with the proportions of separately discharged municipal waste, mixed municipal waste, and construction

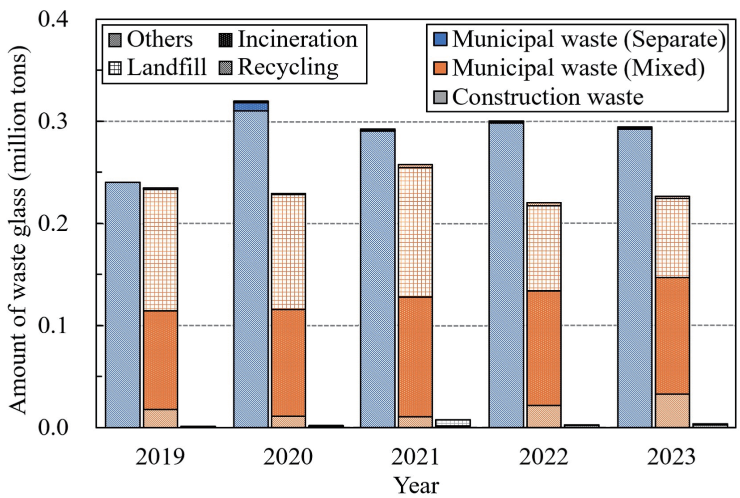


Fig. 1. (Color online) Generation and treatment status of waste glass in South Korea (2019–2023).

waste accounting for approximately 54.9, 44.5, and 0.6%, respectively. Figure 2 shows the treatment ratios according to the waste type. Most glass bottles from separately discharged municipal waste are reused, and broken glass is typically recycled as cullet for new glass production, resulting in a very high recycling rate. In contrast, mixed municipal waste included a wide variety of glass types and colors, resulting in a recycling rate of 8.1%. Among the non-recyclable waste glasses, materials with minimal contamination are mostly landfilled owing to their high melting points. Waste glass with a high impurity content is incinerated because impurity removal is difficult and separation is inefficient. This approach is intended to prevent the secondary environmental pollution that can occur if such waste is landfilled without pretreatment. In contrast with municipal waste, construction waste is managed separately and contains minimal contaminants. Consequently, approximately half of the waste glass from construction sources is recycled, whereas the remainder is landfilled because of its limited recyclability.

Although South Korea maintains a relatively high annual waste glass recycling rate of 58.31%, 41.18% of waste glass is still disposed of in landfills and incineration. Recycling waste glass that is otherwise destined for incineration is technically feasible; however, it requires complex processes, such as washing, drying, and separation. Consequently, despite the potential environmental benefits of recycling, the overall carbon emissions may exceed those of NS.(12) In contrast, much of the waste glass destined for landfill is not disposed of because of a lack of recycling value but rather because it is unsuitable for conventional glass recycling processes. Therefore, in this study, we focused on evaluating the feasibility of diverting waste glass destined for landfill into sustainable fine aggregates for the production of boundary blocks, with a particular focus on carbon emissions and cost reduction. The recycling of waste glass destined for incineration into GS is beyond the scope of this study and remains a subject for future research.

2. Materials and Methods

To quantitatively assess the environmental sustainability of recycled rather than landfilled waste glass, LCA is required. LCA, standardized under ISO 14040, is an internationally

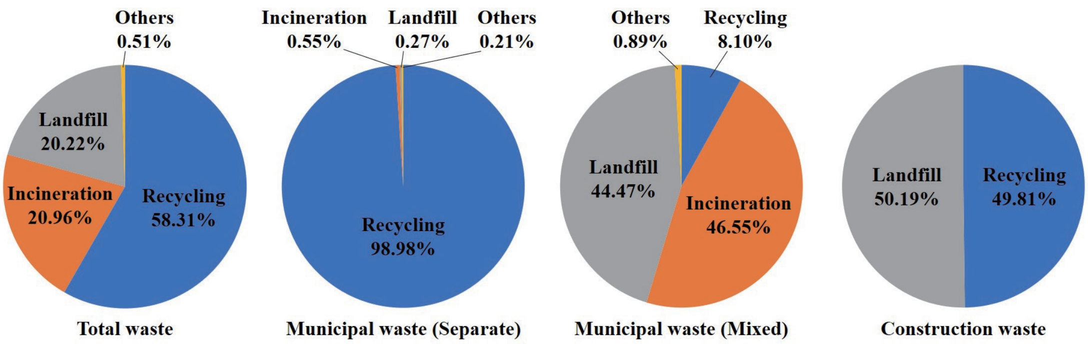


Fig. 2. (Color online) Treatment proportions by waste type.

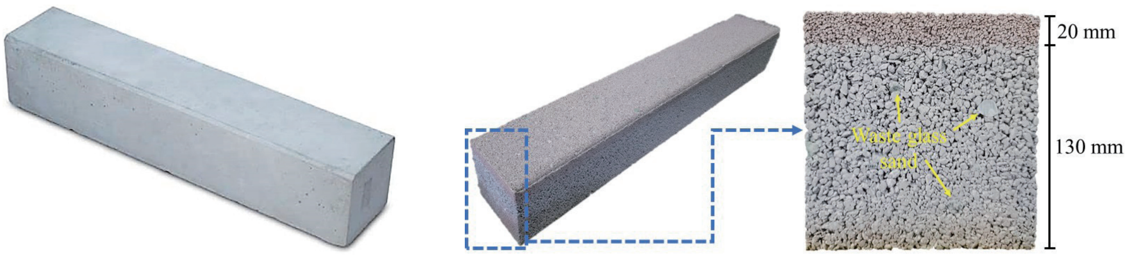
recognized method for evaluating environmental impacts by analyzing resource inputs and emissions throughout a product's lifecycle. To date, most LCA studies have focused on mass-produced construction materials such as concrete. In contrast, relatively few studies have addressed building products, such as paving, permeability, and boundary blocks, owing to their smaller production scale. This gap is attributed to the high demands of LCA in terms of specialized personnel, time, cost, and commercial software. Therefore, in this study, a modular LCA (LCA-m) approach that offers a simplified yet practical framework suitable for application in small and medium-sized enterprises (SMEs) is adopted.(15)

LCA-m adopts the same procedural structure as ISO 14040, which involves defining the study's objectives and scope, compiling a life cycle inventory (LCI), evaluating the environmental impacts, and interpreting the results. However, in contrast with conventional LCA, LCA-m is structured to be implementable without the need for complex commercial software. In this approach, the base LCI is primarily developed using established databases and existing literature. In contrast, the consumption of resources such as water, fuel, and electricity during the manufacturing of building products is quantified through field investigations and integrated into the inventory. Rather than addressing a wide range of environmental impact categories, LCA-m selects key indicators that are directly relevant and practically useful for SMEs. This method enables companies to gradually accumulate experience and build the capability to conduct full-scale LCAs while providing policymakers with the empirical data necessary for promoting sustainable production and management strategies. Consequently, LCA-m aims to demonstrate the potential for reducing environmental impacts through accessible and feasible assessment methods tailored to the SME context.

2.1 Goal and scope

The primary goal of this LCA-m study is to evaluate the environmental and economic impacts of a newly developed permeable boundary block (PB) for SMEs compared with a traditional boundary block (TB). In this context, the potential environmental and economic impacts of incorporating waste glass recycled as GS into PB, specifically using waste glass that would otherwise be landfilled, are investigated. The product system under consideration is a boundary block widely used in South Korea and globally to demarcate different road types. Although boundary blocks are typically installed with paving blocks, asphalt concrete, and a subbase concrete infill, only the boundary block was considered in this study. Its primary function is to provide visual and physical separation between different types of pavement. The functional unit was defined as a single block measuring 150 mm × 150 mm × 1000 mm, as shown in Fig. 3. TB and PB share the same dimensions, but PB is designed as a permeable product consisting of a surface layer and a base layer, with GS incorporated only into the base layer [Fig. 3(b)].

The system boundaries for the LCA-m analysis of TB and PB are shown in Fig. 4. The life cycle of a boundary block includes seven stages: raw material production, raw material transportation, block production, distribution to the site, construction, maintenance, and end of life. To meet the objectives of LCA-m, the system boundary was defined as cradle-to-gate,



(a) (b)

Fig. 3. (Color online) Boundary blocks: (a) traditional type and (b) permeable type with cross-sectional view.

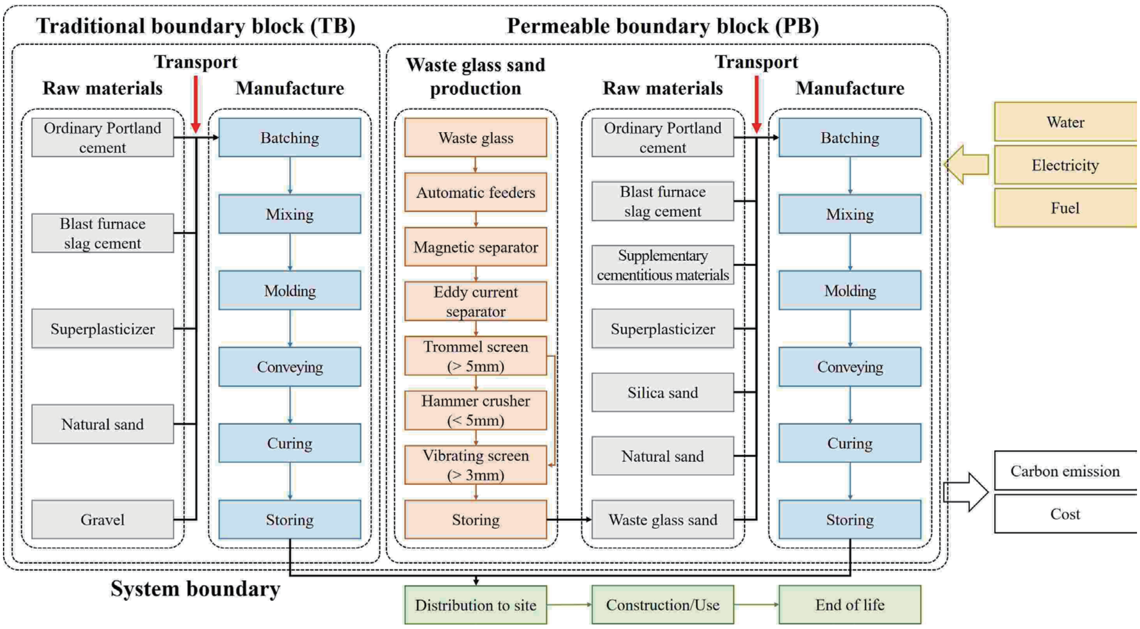


Fig. 4. (Color online) Life cycle of boundary blocks and system boundary.

encompassing only the flow of resources from raw material production to block manufacturing. For the life cycle impact assessment (LCIA), carbon emissions (kg CO_2) were selected as the primary environmental indicators, whereas life cycle cost (LCC) was adopted for economic analysis. Although LCC follows a procedural structure similar to that of LCA, it considers economic factors, such as raw material costs, electricity and fuel consumption, and labor forces, rather than environmental impact.[16] The focus on carbon emissions as the primary environmental indicator aligns with South Korea's low-carbon product certification system, which plays a significant role in enhancing the market competitiveness of SME products. This system offers regulatory advantages, such as the priority purchasing of certified products, thereby directly supporting business operations.

2.2 Base and comparison cases

To analyze the environmental and economic impacts of different types of boundary block, a base case should be defined. In this study, the base case was established as a TB made of ordinary Portland cement (OPC), referred to as TB_O. The mixture proportions of TB_O are presented in Table 1. A polycarboxylate-based superplasticizer (SP) was used to ensure the product quality of the block. Other chemical admixtures such as retarders and pigments, which are occasionally used depending on the application, were excluded from the analysis because of their variability. In addition to TB_O, an alternative base case was considered: a low-carbon TB (TB_S), where OPC was replaced with blast furnace slag cement (BFSC), reflecting the current recommendations to substitute cement in building products in response to climate change.

Owing to climate change, urban flooding caused by heavy rainfall has become increasingly frequent worldwide, prompting various countries to adopt permeable pavement systems.(16) In South Korea, the capital city of Seoul mandates using permeable blocks to address urban flooding. Accordingly, PB, in this study, is defined as a case for comparison with base cases. For detailed analysis, comparison cases were further categorized as PB_O (PB using OPC), PB_S (PB using BFSC), and PB_S_GS (PB using both BFSC and GS). The SCMs used in PB include ground-granulated blast-furnace slag (GGBS), fly ash (FA), silica fume (SF), and calcined gypsum (CG), which are blended in specific proportions. These proportions are considered confidential business information by SMEs producing blocks and are therefore not disclosed. This constraint aligns with a distinctive feature of the LCA-m approach.(15)

Table 2 presents the mechanical properties of the base and comparison cases. PBs exhibit a lower density than TBs because of their higher porosity, which is necessary to ensure permeability. When 20wt% of NS was replaced with GS in PBs, both the density and weight decreased slightly. This was attributed to the increase in porosity caused by the angular shape of the GS particles. According to the Korean Standard KS F 4006, boundary blocks are required to

Table 1
Mix design of boundary block units (by weight).

Materials	Traditional boundary block1)		Permeable boundary block2)		
	TB_O (%)	TB_S (%)	PB_O (%)	PB_S (%)	PB_S_GS (%)
Ordinary Portland cement (OPC)	14.5	0.0	6.8	0.0	0.0
Blast furnace slag cement (BFSC)	0.0	14.5	0.0	6.8	6.8
Supplementary cementitious materials (SCMs)	0.0	0.0	10.9	10.9	10.9
Water (W)	4.3	4.3	0.9	0.9	0.9
Natural sand (NS)	34.4	34.4	77.2	77.2	61.8
Silica sand (SS)	0.0	0.0	4.1	4.1	4.1
Waste glass sand (GS)	0.0	0.0	0.0	0.0	15.4
Gravel (G)	46.6	46.6	0.0	0.0	0.0
Superplasticizer (SP)	0.1	0.1	0.1	0.1	0.1

1) TB_O: Traditional boundary block using ordinary Portland cement; TB_S: Traditional boundary block using blast furnace slag cement.
2) PB_O: Permeable boundary block using ordinary Portland cement; PB_S: Permeable boundary block using blast furnace slag cement.
PB_S_GS: Permeable boundary block using blast furnace slag cement and waste glass sand (20wt%).

Table 2
Mechanical properties of boundary blocks.

Mechanical properties	TB_O	TB_S	PB_O	PB_S	PB_S_GS
Density (kg/m^3)	2266.7	2266.7	1911.1	1911.1	1895.6
Weight (kg)	51.0	51.0	43.0	43.0	42.7
Flexural strength	7.3	6.6	6.2	5.6	5.5
Permeability coefficient (cm/s)	—	—	0.05	0.05	0.06

satisfy a minimum flexural strength of 4 MPa, and all blocks used in this study satisfied this requirement. In addition, PBs must also comply with KS F 4419, which mandates a minimum coefficient of permeability of 0.01 cm/s and a flexural strength of at least 5 MPa. All PBs met these criteria; however, their flexural strength decreased in the order PB_O > PB_S > PB_S_GS. This reduction is considered to be a result of the relatively slower reactivity of BFSC and the increased porosity induced by GS. Nevertheless, the smooth surface of GS contributed to an increase in permeability, suggesting that the appropriate use of GS in permeable products may offer a feasible recycling strategy.(17)

2.3 LCI

To conduct both the LCIA and LCC analyses, an LCI must first be developed. A conventional LCI typically tracks all input and output flows within a product system, including raw materials, energy, water, and emissions to air, water, and soil, often utilizing specialized software such as GaBi or SimaPro. However, in this study, the LCI database (DB) was constructed without such software, in alignment with the LCA-m approach, as summarized in Table 3. The carbon-emission factors for the raw materials and energy types were primarily sourced from the government-provided LCI DB (Korea-ECO).(18) When data were unavailable, supplementary values were obtained from relevant literature. In contrast, cost data are rarely available in existing databases; therefore, literature sources were used wherever possible, and additional data were collected through field investigations when necessary.

As GS is not a commonly used material, constructing an LCI DB presents considerable challenges. Researchers in several studies have conducted LCAs on the recycling process of waste glass into GS, highlighting that the required processing steps vary depending on the condition of the waste glass, and that these variations significantly affect both carbon emissions and costs.(12,16) Therefore, to ensure reliable LCIA and LCC results, in this study, we developed an LCI DB for GS production through field investigations. The target material was waste glass, which could not be recycled owing to its mixed types, despite containing minimal impurities. Because the waste glass collected by IPCs originates from diverse sources, transportation distances vary widely. Additionally, waste glass destined for landfill is often temporarily stored and sometimes reused as road or ground fill. Accordingly, in this study, the waste glass used for GS production was assumed to have been retrieved from storage facilities. Consequently, the emissions and costs associated with transporting waste glass to IPCs were excluded from the system boundary.

Table 3
LCI DB of raw materials and energy used in the boundary block production (Field: field investigation).

Inventory items		Carbon emissions (kg CO_2)	Data sources	Cost ($USD)	Data sources
OPC (/kg)		0.926	(18)	0.09	(20)
BFSC (/kg)		0.503	(18)	0.08	Field
SCMs (/kg)	GGBS	0.071	(18)	0.05	(20)
	FA	0.027	(19)	0.02	Field
	SF	0.020	(20)	0.90	(20)
	CG	0.141	(21)	3.50	Field
W (/L)		0.0002	(20)	0.0006	(20)
NS (/kg)		0.006	(20)	0.03	(22)
SS (/kg)		0.022	(20)	0.05	Field
G (/kg)		0.004	(20)	0.02	(22)
SP (/kg)		0.010	(22)	3.50	(22)
Diesel (/L)		2.582	(20)	1.09	(23)
Electricity (/kwh)		0.380	(4)	0.11	(4)

The GS production process is illustrated in Fig. 4 and has been described in detail in previous studies.[24] On the basis of the processing of 10 tons of waste glass, the consumption of water, fuel, electricity, and labor was investigated for the transportation, crushing, and storage stages. Ampere meters (JC16F-RMS, J&D Electronics, South Korea) were installed on the control panel of each machine to measure the power consumption of the equipment used in the crushing process.[25] The data were recorded using a data logger (CR1000X; Campbell Scientific Co., Ltd.). The power consumption was calculated using Eq. (1). All equipment operated on three-phase alternating current, and the power factor values provided by the equipment manufacturers (ranging from 0.7 to 0.9) were applied. The average power consumption was derived by measuring the power consumed during the GS production process using 10 tons of waste glass.

$$W = V \times I \times PF \times \sqrt{3} \times 10^{-3} \quad (1)$$

Here, W is the power consumption (kW), V is the alternating current voltage (V), I is the current (A), and PF is the power factor.

To produce boundary blocks, raw materials must be transported to a manufacturing facility, resulting in increased carbon emissions and increased costs. It was assumed that all materials are transported by truck, and the carbon emissions associated with truck transport were set at 0.1924 kg CO_2/ton·km.[18] Transport costs were calculated using Eq. (2).[26] Truck speed and traffic conditions were not considered. Although most raw materials are sourced from nearby locations (within 10 km) of the block manufacturing facility, materials such as FA and SP are transported from distant sources. Therefore, the average transport distance was assumed to be 50 km in this study.

$$Cost\ T = \sum_{i} \left[\left(M_{(i)} / L_t \right) \times \left(d / e \right) \times Fuel\ price\ F \right] \quad (2)$$

Here, $Cost\ T$ is the cost of transporting materials ($USD), $M_{(i)}$ is the amount of the (i)th material used for the boundary block (kg), L_t is the transportation load (kg), d is the transportation distance (km), *e* is the fuel efficiency (km/L), and *Fuel price F* is the cost of fuel (diesel) ($USD/L).

A field investigation was conducted to quantify the consumption of water, fuel, and electricity to calculate the carbon emissions and costs associated with the production of the boundary blocks. The overall manufacturing process, from raw material transportation to the completion of blocks prior to their distribution to the site, is illustrated in Fig. 5. Although the transportation of raw materials from the delivery point to the batching system hopper is sometimes treated as a separate step in the manufacturing process, in this study, we consider it to be part of the raw material transportation stage.

The raw materials were supplied in proportions according to the mix design of each boundary block type, followed by dry mixing and hoisting into a wet mixing system. The dry mix was combined with water, modified with an SP to secure workability, and then discharged in the required amounts into the molding system. The block-forming machine produces blocks via vibration compaction, and the compaction procedures differ between TB and PB. Because TB does not have a separate surface layer, it was compacted once by vibration for 5 s. Conversely, PB includes a surface layer and requires stronger compaction owing to its high porosity [Fig. 3(b)]. Therefore, it underwent two vibration compaction steps: 3 s after casting the base layer and 10 s after casting the surface layer. The block-forming machine produced approximately 2000 TBs and 1600 PBs during an 8 h period. The production rate of PB is low because of its two-layer casting and dual-compaction processes. After molding, the blocks were placed on pallets and transported to a curing chamber. To satisfy the curing requirement of 500 °C·day specified in KS F 4006, the blocks are steam-cured at 35 °C for one day. The cured blocks were then transferred to the storage system, packed, and stored for a minimum of seven days to ensure sufficient strength development.

In this study, only the direct energy consumed during the production of boundary blocks was considered. The indirect energy, material inputs, and emissions related to the construction of manufacturing facilities and equipment were excluded. Additionally, waste and air emissions

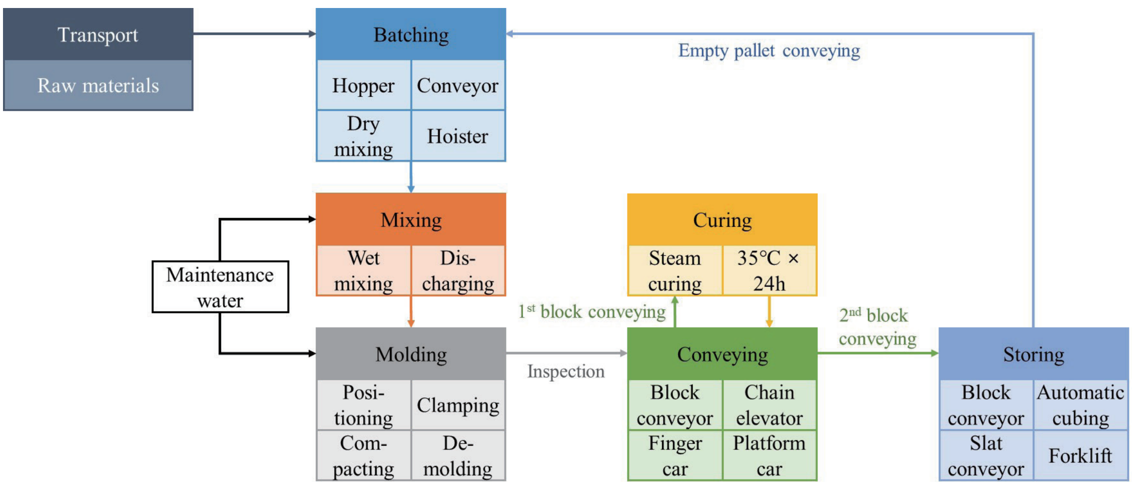


Fig. 5. (Color online) Production process of boundary blocks.

generated during the block production process can vary significantly, even within the same process, potentially affecting the results of the LCIA and LCC. Therefore, these factors were excluded from the system boundaries used in this study.(16,27) Field data for the boundary block manufacturing process were obtained from Company C (Jecheon-si, South Korea), which produces both TB and PB. The production line is fully automated and operated in a central control room, enabling the efficient monitoring of energy consumption. Therefore, unlike in the GS production process, separate measurements of power consumption were not conducted.

3. Results

3.1 Recycling process of GS

Table 4 presents a summary of the resource inputs, carbon emissions, and costs associated with the waste glass recycling process. The waste glass used in this study was taken from a stockpiled material that, despite containing minimal impurities, was set aside for landfill

Table 4
LCI of waste glass recycling process.

Production system category		Input	Quantity	Unit	Carbon emissions (kg CO_2)	Cost ($USD)	Verification (kwh) (Ref.)
Feedstock		Waste glass	10	ton	—	—	—
Transportation		Diesel	4.1	L	10.6	4.5	—
		Labor force	2	man	—	14.7	—
Remove foreign substance		Water	50	L	0.01	0.03	—
		Labor force	1	man	—	7.4	—
Feeding	Automatic feeder	Electricity	2.5	kwh	1.0	0.3	2.5(28)
Separating	Magnetic separator	Electricity	11.2	kwh	4.3	1.2	11.8(28)
	Eddy current separator	Electricity	4.6	kwh	1.7	0.5	4.4(28)
Screening	Trommel screen	Electricity	8.4	kwh	3.2	0.9	7.4(28,29)
	Linear vibrating screen	Electricity	7.8	kwh	3.0	0.9	5.2(30)
Crushing	Hammer crusher	Electricity	27	kwh	10.3	3.0	15.4(31–33)
Handling	Conveyor belt	Electricity	0.9	kwh	0.3	0.1	1.0(28,34)
Management (25% of labor force)					—	5.5	
Maintenance (7% of equipment and $3/h for building)					—	5.9	
Cost recovery					—	30.0	
Tax (9.7% of supply cost)					—	7.3	
Sum (8 ton/h of GS)					34.3	82.1	
LCI DB of GS (/kg)					0.0043	0.0103	

because of the presence of various types of glass. To transport 10 tons of waste glass to the feeder, one excavator and one truck were used, and 50 L of water was used to remove dust and other fine impurities. The transported glass was fed at a controlled rate and subjected to primary separation using magnetic and eddy current separators to remove metallic elements, such as bottle caps. Residual contaminants, such as plastic and label paper, were then removed manually. Subsequently, the waste glass was screened using a 5 mm mesh trommel, and particles larger than 5 mm were crushed using a hammer mill equipped with a 5 mm screen.

Glass particles smaller than 5 mm were further screened using a linear vibrating screen to collect only 3–5 mm particles. Throughout the process, the material was automatically transported via conveyor belts. The entire operation took 1 h to produce 8 tons of GS. The remaining two tons consisted of by-products and particles smaller than 3 mm, which had been separated by type and were therefore considered recyclable. For example, glass particles smaller than 3 mm can be used as roadbase materials.[12] However, additional processing may be required depending on the specific recycling path, which can significantly affect carbon emissions and costs. In this study, it was assumed that no further processing was conducted on these 2 tons of material; therefore, no additional emissions or costs were considered. Moreover, processes such as landfill were excluded under the assumption that these materials remain recyclable.

To validate the measured energy consumption of the equipment used in the waste glass recycling process, the results were compared with those of previous studies.[28–34] While the levels of energy consumption during feeding, separating, and handling stages showed good agreement, some discrepancies were observed in the screening and crushing stages. These differences are likely due to variations in material type and processing conditions, particularly particle size, which significantly affect energy requirements. Glass, in particular, requires a higher energy input for processing than other materials.[28] Additionally, Mourou *et al.* reported an energy consumption of 11.1 kWh/ton for producing GS with particle sizes of 0–3 mm.[35] Therefore, the 7.8 kWh/ton measured in this study for producing relatively large GS particles (3–5 mm) is considered reasonable.

Generally, IPCs in South Korea receive recyclable waste glass feedstock at a price of \$20–40/ton and process it for sale to glass manufacturers.[36] However, waste glass mixed with different colors, types, and impurities requires complex sorting processes, resulting in a negative market value.[37] The waste glass used in this study consisted of landfill material with mixed colors and types but minimal impurities. As such, it is typically managed through delegated treatment, with the waste generator bearing the disposal cost. Accordingly, the market value of the waste glass destined for landfilling was considered negligible, and the feedstock cost was set to zero. Labor costs were based on the Korean minimum wage of \$7.36/h, and the costs associated with the management and maintenance of the GS recycling process were estimated using economic indicators reported in previous studies.[37] Cost recovery includes the initial investment, depreciation, and profit margins, and the values provided by the IPCs were used. Taxes were set at 9.7%, reflecting a 10% standard value-added tax minus a 0.3% tax credit for waste glass recycling.

Consequently, the carbon emissions and costs associated with recycling waste glass into GS were calculated to be 0.0043 kg CO_2/kg and \$0.0103/kg, respectively. To validate the constructed

LCI DB for GS, the calculated carbon emissions and costs were compared with previous studies. Tushar *et al.* reported carbon emissions of 0.0141 kg CO_2/kg for GS production, excluding the recycling of by-products.(12) Of this total, 0.01 kg CO_2/kg was attributed to the landfilling of non-recyclable by-products, whereas 0.0041 kg CO_2/kg was related to washing, sorting, and crushing the waste glass. Yuan *et al.* reported carbon emissions and costs of 0.039 kg CO_2/kg and \$0.082/kg, respectively, for GS production.(13) The discrepancy between their results and those of this study is attributed to several factors: their assumed transportation distance was 200 km, the washed waste glass was dried using natural gas, and the feedstock contained a high impurity content (22%), requiring more complex separation steps. These assumptions substantially increase carbon emissions and costs. Furthermore, in their analysis, the cost of feedstock was \$61.55/ton, accounting for 81% of the total production cost. Assuming a zero-cost feedstock, the unit cost of GS would decrease to \$0.02/kg.

These differences in the results of the GS recycling processes indicate that the conditions of the waste glass feedstock are critical factors. In this study, the carbon emissions and costs associated with producing GS from waste glass destined for landfill were evaluated, demonstrating that GS has sufficient potential to serve as a sustainable construction material compared with NS (Table 3). However, waste glass destined for incineration, which typically contains more impurities and contaminants, requires additional washing and separation steps that likely result in higher carbon emissions and costs. Therefore, further research is needed to explore effective recycling strategies for waste glass intended for incineration.

3.2 Production of boundary blocks

As a result of analyzing the resource inputs for boundary block production, the consumptions of electricity, diesel, and water per block were found to be 1.17 kWh, 0.01 L, and 3.69 L for TB, and 1.61 kWh, 0.01 L, and 1.08 L for PB, respectively. The higher power consumption for PB was attributed to the need for two separate mixers, one for the base layer and the other for the surface layer, as well as the two casting and vibration compaction steps required for each block (Fig. 3). In contrast, the water consumption of TB was approximately three times higher than that of PB. This difference was due to the higher water demand in the TB mix design (Table 1), along with the greater use of water for equipment cleaning and maintenance during block production. Among the various stages of block production, the curing stage accounts for the largest share of power consumption, representing 64% for TB and 55% for PB. The production process involved three workers: a general supervisor, a control room operator, and a forklift driver.

Recycling waste glass into GS contributes to reducing the consumption of natural resources and prevents the environmental impacts and costs associated with landfilling. In this study, the scenario without GS assumes that waste glass is not recycled but is landfilled. The landfilled material included both the quantity of waste glass equivalent to the GS used in block production and the associated by-products (20 wt.%) that would otherwise have been removed through the recycling process. Waste glass is transported from the IPC to a landfill site, and a landfill fee of \$0.02/kg is incurred for disposal.(38) Therefore, the total landfill-related cost is calculated as

\$0.04/kg, accounting for both the disposal cost and the landfill fee. Carbon emissions from landfilling were set at 0.012 kg CO_2/kg, based on the national LCI DB.(18) These landfill-related emissions and costs are reflected in the scenario of boundary block production without GS.

The carbon emissions associated with boundary block production are presented in Fig. 6. Among carbon emission sources, including raw materials, transport, manufacturing, and waste glass disposal, raw materials have the most significant impact. TB_O exhibited the highest carbon emissions at 9.19 kg CO_2/block, owing to the high proportion of OPC [Fig. 6(b)]. This value is consistent with that of previous studies, which reported carbon emissions of 7.50–10.92 kg CO_2/block for concrete blocks made with OPC.(16,27) Replacing OPC with BFSC reduced the emissions by approximately 39%. In comparison, PB_O resulted in 4.40 kg CO_2/block, which is 52% lower than that of TB_O, owing to the significantly reduced carbon emissions of raw materials resulting from OPC substitution with SCMs. Furthermore, PB_S_GS produced using both BFSC and GS reduced the carbon emissions by 68 and 33%, respectively, compared with TB_O and PB_O. However, despite the benefits of waste glass recycling, PB_S_GS exhibited only a marginal difference from PB_S in terms of carbon emissions. This is because the GS replacement ratio was limited to 20 wt% to prevent the deterioration of mechanical properties.(24)

Figure 7 presents the costs associated with the production of boundary blocks. Similar to the carbon emission results, raw materials were found to have the most significant impact on the overall cost. However, the production costs of PB are higher than those of TB. This is primarily due to the greater energy required during the manufacturing process for PB and the high costs of SF and CG used as SCMs to ensure quality while reducing cement usage [Fig. 7(b)]. Among all block types, PB_O showed the highest cost of \$3.56/block, which is attributed to the use of OPC, which is more expensive than BFSC. The cost of PB_S_GS was \$2.99/block, which is 15% lower than that of PB_S. This cost reduction is due to the substitution of NS with GS, as GS is less expensive and incurs no waste glass disposal costs. Despite these benefits, TB_O exhibited a lower production cost (\$2.89/block) than PB_S_GS.

To validate the calculated cost of TB_O, the results were compared with those of previous studies on the concrete block production costs. Yuan *et al.* reported a production cost of \$1.47/block for concrete blocks, which is lower than the value calculated in this study.(16) The

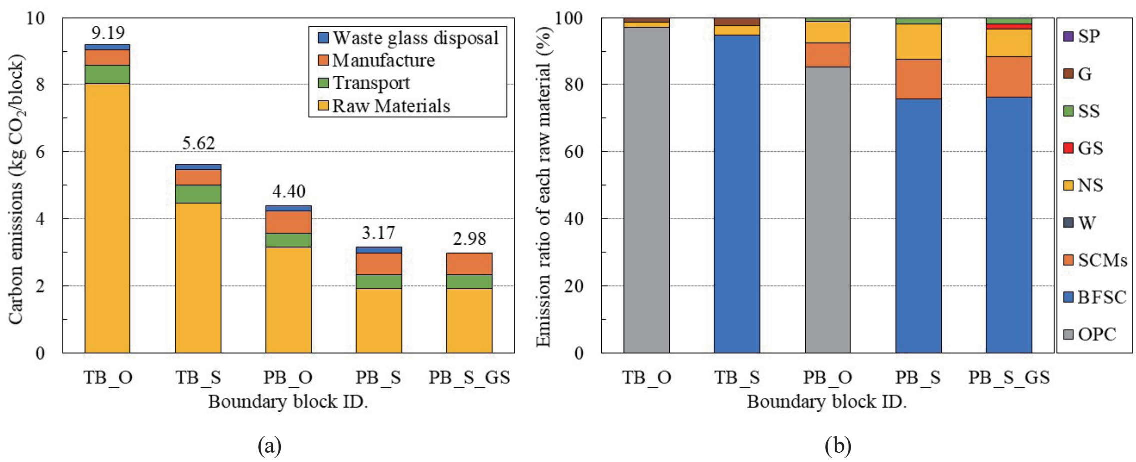


Fig. 6. (Color online) Carbon emissions of boundary blocks: (a) block type and (b) emission ratio of raw materials.

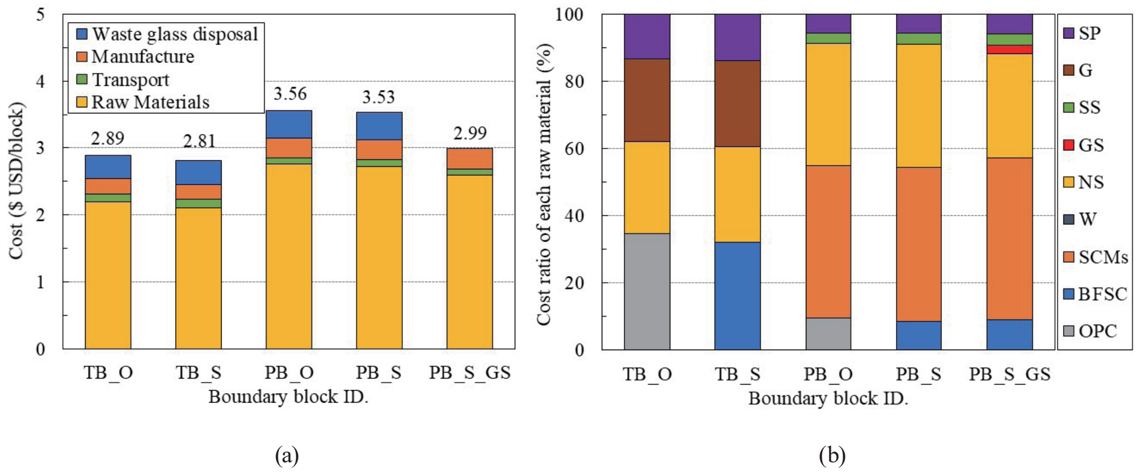


Fig. 7. (Color online) Costs of boundary blocks: (a) block type and (b) cost ratio of raw materials.

discrepancy arises because their analysis did not account for the transportation of raw materials, water consumption, waste glass disposal, and the use of SP. Additionally, no energy consumption for curing was considered in their study. When these factors are excluded from this study, the block production cost decreases to $2.04/block. Considering further differences in concrete mix design and manufacturing methods, the cost of TB_O calculated in this study appears to be within a reasonable range.

4. Discussion

Compared with traditional boundary blocks, the low-carbon permeable boundary block incorporating GS demonstrated effective reductions in carbon emissions. Specifically, PB_S_GS reduced the emissions by approximately 68 and 47% compared with TB_O and TB_S, respectively. In contrast, compared with PB_S, the reduction was only approximately 6%, indicating that the replacement of NS with GS in block production may have a limited impact on emission reduction at the unit product level. However, according to South Korea's low-carbon product certification system, which requires a minimum reduction rate of 3.3% compared with similar products, PB_S_GS qualifies for certification. Moreover, the benefits of GS recycling became more apparent when assessed on a national scale rather than per block. The amount of waste glass landfilled annually in South Korea is estimated to be 35495 tons, approximately 28396 tons of which can be recycled as GS to replace NS (Fig. 1). This would lead to an annual reduction of approximately 674 tons in carbon emissions. If this amount was converted into the Korea Credit Unit (KCU) through an external project to reduce carbon emissions, it could generate approximately $4891 in revenue.

However, from the perspective of SMEs, the change in production cost is often a more critical factor than the carbon emission reduction benefit. In this study, the cost of landfilling waste glass is reflected in the production cost of the boundary blocks. However, manufacturers do not bear the waste glass treatment costs. Excluding these costs, the production costs of TB_O and TB_S were $2.54/block and $2.46/block, which were 15 and 17% lower than those of PB_S_GS, respectively. The cost of PB_S also decreases to $3.12/block, making the difference from that of

PB_S_GS as small as 4%. Furthermore, manufacturers do not receive any direct financial benefits such as tax reductions when using recycled GS. Under such circumstances, the incentive to use recycled GS can become unclear, because its quality may not be fully guaranteed. Therefore, local governments need to establish policies that convert the benefits of waste glass recycling into tangible economic incentives for manufacturers. Such policies would help promote the use of recycled materials, thereby mitigating the regional conflicts and environmental issues associated with landfill disposal.

In this study, the environmental and economic impacts of boundary blocks incorporating GS recycled from waste glass were analyzed using a simplified LCA-m approach. However, this study has several limitations. First, only waste glass destined for landfill was considered among unrecycled waste glasses. In addition, the recycling of by-products, such as GS particles smaller than 3 mm, which are generated in the GS manufacturing process, was not considered. Furthermore, the environmental impacts of waste outputs such as wastewater and air emissions were excluded from the system boundary. Future research should expand the scope to include all types of unrecycled waste glass and incorporate treatment scenarios for by-products and waste into the LCA system boundary. Second, although the environmental and economic impacts of boundary blocks from a cradle-to-gate perspective were evaluated in this study, a cradle-to-grave analysis that includes the end-of-life stages is necessary. In particular, differences in maintenance requirements associated with the permeability performance of installed PBs may significantly affect LCA outcomes. Lastly, the LCA-m method applied in this study was designed for accessibility by SMEs and thus did not include comprehensive impact categories, quantitative uncertainty assessments, or sensitivity analyses. In addition, the LCI data were collected from a single recycling facility under specific operational conditions. Therefore, the results may vary depending on regional factors such as the energy mix, transportation distance, and process efficiency. To enhance the reliability of the LCA results, future studies should verify and refine LCI parameters by collecting data from multiple facilities across different regions and adopt a systematic LCA approach based on specialized software that enables more detailed evaluations.

5. Conclusion

In this study, the environmental and economic impacts of PB incorporating GS, based on an LCA-m approach suitable for SMEs that may face challenges in conducting a full-scale LCA, were analyzed. In this approach, the base LCI was primarily developed using established databases and existing literature, whereas resource consumption data, such as water, fuel, and electricity, used in the manufacturing of boundary blocks were collected through field investigations and integrated into the inventory.

The analysis showed that recycling landfill-designated waste glass into GS can replace approximately 28396 tons of NS annually in Korea, thus presenting a viable alternative for resource conservation and landfill reduction. The use of GS in PB_S_GS led to carbon emission reductions of approximately 68 and 47% compared with TB_O and TB_S, respectively. Even when compared with PB_S, which used the same binder, a reduction of approximately 6% was observed. These results meet the criteria of Korea's low-carbon product certification system, which requires a minimum reduction of 3.3% compared with similar products and can help promote sustainable procurement.

However, the production costs of PB_S_GS were 3 and 6% higher than those of TB_O and TB_S, respectively, and were 15% lower than that of PB_S. This suggests that, despite its environmental benefits, GS does not necessarily offer a clear economic advantage to manufacturers. Considering that actual block manufacturers do not incur costs for waste glass disposal, a comparative scenario excluding these costs shows that PB_S_GS is 17% more expensive than TB_S and only 4% cheaper than PB_S. These findings suggest that the limited cost advantage may not sufficiently incentivize SMEs to use GS, particularly when the quality guarantee is unclear. Therefore, in addition to supporting such low-carbon product certification, the benefits of recycling waste glass should be provided as tangible economic incentives for manufacturers.

Overall, the results indicated that GS can serve as an effective substitute for NS, thereby contributing to more sustainable construction practices. However, to clearly establish this potential, further research should be conducted using a systematic LCA approach and an expanded system boundary, incorporating a broader range of environmental impact categories, as well as uncertainty and sensitivity analyses. Nevertheless, these results may serve as a useful reference for policy development and design decision making to support sustainable construction practices.

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