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Carbon Dioxide Emission Evaluation of Porous Vegetation Concrete Blocks for Ecological Restoration Projects

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Abstract: The purpose of this study is to determine the mix proportions that can minimize CO_2 emissions while satisfying the target performance of porous vegetation concrete. The target performance of porous vegetation concrete was selected as compressive strength (>15 MPa) and void ratio (>25%). This study considered the use of reinforcing fiber and styrene butadiene (SB) latex to improve the strength of porous vegetation concrete, as well as the use of blast furnace slag aggregate to improve the CO_2 emissions-reducing effect, and analyzed and evaluated the influence of fiber reinforcing, SB latex, and blast furnace slag aggregate on the compressive strength and CO_2 emissions of porous vegetation concrete. The CO_2 emissions of the raw materials were highest for cement, followed by aggregate, SB latex, and fiber. Blast furnace slag aggregate showed a 30% or more CO_2 emissions-reducing effect versus crushed aggregate, and blast furnace slag cement showed a 78% CO_2 emissions-reducing effect versus Portland cement. The CO_2 emissions analyses for each raw material showed that the CO_2 emissions during transportation were highest for the aggregate. Regarding CO_2 emissions in each production stage, the materials stage produced the highest CO_2 emissions, while the proportion of CO_2 emissions in the transportation stage for each raw material, excluding fiber, were below 3% of total emissions. Use of blast furnace slag aggregate in porous vegetation concrete produced CO_2 emissions-reducing effects, but decreased its compressive strength. Use of latex in porous vegetation concrete improved its compressive strength, but also increased CO_2 emissions. Thus, it is appropriate to use latex in porous vegetation concrete to improve its strength and void ratio, and to use a blast furnace slag aggregate replacement ratio of 40% or less.

Keywords: blast furnace slag aggregate; CO_2 emissions; fiber; latex polymer; void ratio; porous vegetation concrete

1. Introduction

Recently, as interest in ecosystem restoration has increased, many studies have been conducted on porous vegetation concrete, a concrete in which a certain amount of cement is replaced with industrial by-products, such as blast furnace slag fine powder, and which uses large rather than small aggregates to form concrete voids [1–4]. Such porous vegetation concrete has decreased mechanical performance and durability due to the larger voids [5–9]. To address this problem, via addition of polymer and stiffening fiber addition, studies have been carried out to improve this concrete's vegetation-promoting ability, physical/mechanical characteristics, and durability [10–17].

A fundamental plan to deal with CO_2 emissions, which influence global warming, has been demanded. It has been concluded that the accumulation of CO_2 in the atmosphere causes climate change, and the establishment of a plan to slow climate change is necessary [13–19]. Currently, the cause of the increasing temperature on Earth is considered to be the use of fossil fuels, which has been an essential element in maintaining contemporary industrial society [13,18,19]. The temperature rise is progressing faster than 'natural' changes, and is expected to further accelerate [13,15,16].

Thus, the concrete industry has been looking for ways to decrease CO_2 emissions to help reduce CO_2 emissions to the atmosphere. Moreover, the cement industry causes significantly more CO_2 emissions than many other industries [13,14]. Indeed, the amount generated globally during the production process of cement has been estimated at ~3% of all CO_2 emissions worldwide [13,14]. Thus, decreasing the amount of cement use is one important method to reduce CO_2 emissions. Currently, the amount of CO_2 emissions released during the production of 1 ton of cement is about 870 kg [13,14]. Therefore, there is an urgent need to minimize the use of cement. If blast furnace slag fine powder can replace cement, this would help to address the problem of global warming [13,14].

In the concrete industry, crushed rocks are also used widely as aggregates [20]. However, crushed rocks are also problematic for the environment and nature, so there is a need to study alternative aggregates [18]. Blast furnace slag aggregate is among the potential replacement materials [18]. Blast furnace slag aggregate, or blast furnace slag fine powder, is a by-product of the steel industry and is classed a waste product [18]. Thus, if blast furnace slag aggregate could be used instead of crushed rocks, this would be effective in terms of not only conferring environmental protection, but also for resource recycling and CO_2 emissions-reducing effects [10–13,15,16].

Porous vegetation concrete can be used for river/shore protection; furthermore, because water, air, and plant roots can freely penetrate through continuous voids, plant roots can enter and grow in this concrete [10,11,18]. Also, porous vegetation concrete allows full greening and promotes the accumulation of sediment and soil, which can lead to the regeneration of plants [10,11,18]. When plants are cultivated in concrete, they may not grow due to the high alkali content of the moisture in the concrete, lack of space for roots or germination, low water penetration, and, consequently, poor nutrient availability [10,11,18]. Thus, "vegetation concrete" is a porous material that encourages the growth of plants by introducing nutrient-containing water into voids [10,11,18]. Due to soil compartments on the porous concrete surfaces, there is space for germination, drying, and even fertilizer supplies after plant germination [10,11,18]. The required properties of vegetation concrete are that plants can grow inside the concrete in accordance with the basic mechanical properties of concrete [10,11,18]. Important characteristics by which to assess porous vegetation concrete are the compressive strength and void ratio [10,11,18]. A sufficient void ratio encourages the growth of plant roots, while compressive strength determines the stability of the concrete, which should not be compromised by the growth of plant roots [10,11,18]. Porous vegetation concrete is required by the Ministry of Environment of Korea to have a void ratio of 25% or more and a compressive strength of 15 MPa or more [19,20].

In this study, the test variables were blast furnace slag aggregate replacement rate of crushed aggregate (0%, 20%, 40%, 60%, and 100%), latex content (0 kg/m^3 and 6.12 kg/m^3), and fiber reinforcement content (0 kg/m^3 and 1.41 kg/m^3). The tests carried out compressive strength, void ratio, and CO_2 emissions analysis. The relationship between compressive strength, void ratio, and CO_2 emissions according to the mixture was analyzed to determine the mix proportions that can minimize CO_2 emissions while satisfying the target performance of porous vegetation concrete.

2. Materials and Methods

2.1. Materials

The blast furnace slag cement used here had a blast furnace slag replacement ratio of 60% and the physical/chemical properties are listed in Table 1. Aggregates with a maximum size of 25 mm were used as "coarse aggregates" (Figure 1a). Their physical properties are shown in Table 2. Blast furnace slag aggregates are 25–28 mm in size (Figure 1b). Physical and chemical properties of the blast furnace slag aggregates are shown in Table 1. Their density was 2.36 g/cm^3, the absorption ratio was 5%, and the unit volume mass was 1.56 kg/L. Natural jute fiber was used as a reinforcing fiber. The characteristics and geometry of natural jute fiber are shown in Table 3 and Figure 1c. Styrene butadiene (SB) latex (Figure 1d) was also used and its properties are listed in Table 4.

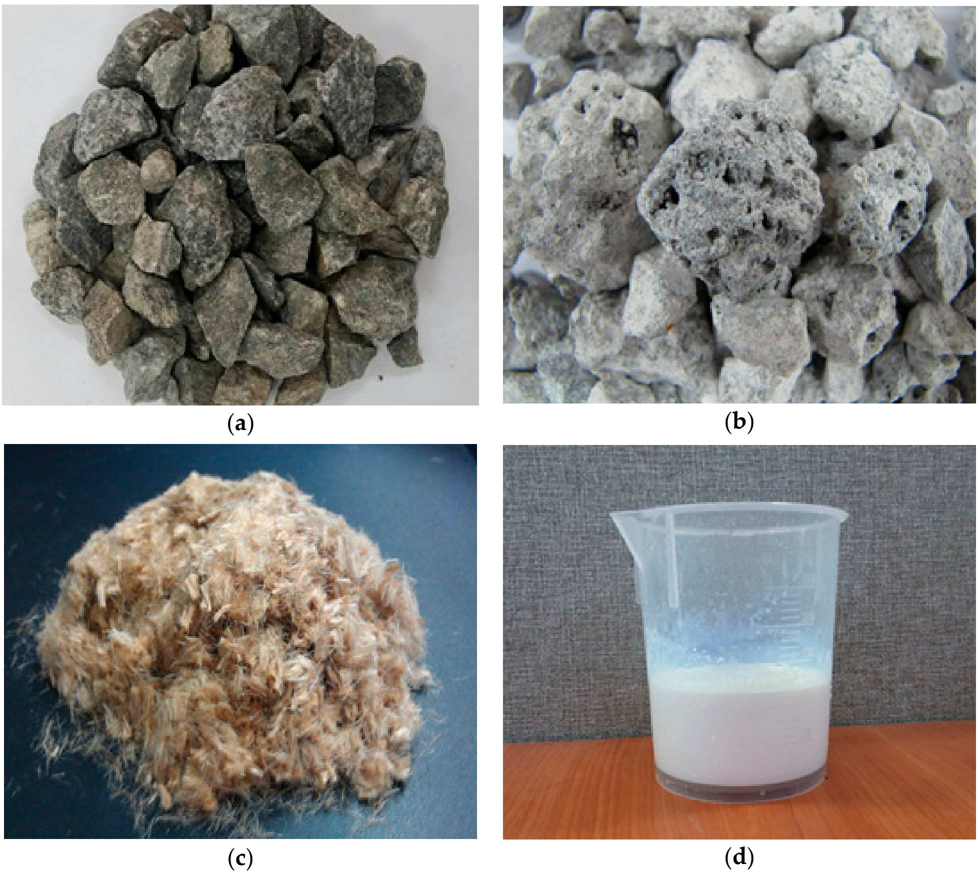

Figure 1. Materials. (**a**) Crushed aggregate; (**b**) Blast furnace slag aggregates; (**c**) Jute fiber; (**d**) Styrene butadiene (SB) latex.

Table 1. Physical and chemical properties of blast furnace slag cement and aggregate.

	Blast Furnace Slag Cement			**Blast Furnace Slag Aggregate**	
Physical properties	Fineness (cm^2/g)		4330	Density (g/mm^3)	2.36
	Density (g/mm^3)		3.02		
	Stability (%)		1		
	Setting time (Gillmore needle)	Initial set (h:min)	4:25	Water absorption ratio (%)	5
		Final set (h:min)	6:15		
	Compressive strength (MPa)	3 day	20.6	Unit volume weight (kg/m^3)	1.56
		7 day	29.8		
		28 day	54.5		

		Chemical Compositions (%)				
Chemical properties	**Ignition Loss (%)**	MgO	SO_3	Fe_2O_3	CaO	SO_3
	0.5	2.9	2.9	0.1	23.8	1.7

Table 2. Physical properties of crushed aggregate.

Density (g/mm^3)			Absorption (%)	Fineness Modulus
Bulk	Saturated Surface-Dry	Apparent		
2.80	2.65	2.83	0.35	6.92

Table 3. Properties of jute fibers.

Elastic Modulus (GPa)	Density (g/cm^3)	Fiber Length (mm)	Fiber Diameter (mm)	Tensile Strength (MPa)	Surface
61	1.26	3	0.015	510	Hydrophilic

Table 4. Properties of SB latex.

Solids Content (%)	Styrene Content (%)	Butadiene Content (%)	pH	Density (g/cm^3)	Surface Tension (dyne/cm)	Particle Size (Å)	Viscosity (cps)
49	34 ± 1.5	66 ± 1.5	11.0	1.02	30.57	1700	42

2.2. Mix Proportions

Through a data survey and analysis of existing porous vegetation concrete, reinforcing fiber and latex were used to improve the strength, standard mixing, and fiber reinforcing properties of the concrete. The blast furnace slag aggregate replacement ratio for reducing CO_2 emissions was 20%–100%, and the mix design of the porous vegetation concrete is shown in Table 5. This study selected a mix that would reduce CO_2 emissions while still satisfying environment index certification standards (compressive strength of at least 12 MPa, void ratio of 25%).

Table 5. Mixture design of porous vegetation concrete.

<table>
<tr><th rowspan="3">Type of Mix</th><th colspan="6">Unit Weight (kg/m³)</th></tr>
<tr><th rowspan="2">Water</th><th rowspan="2">Blast Furnace Slag Cement</th><th colspan="2">Aggregate</th><th rowspan="2">Fiber</th><th rowspan="2">Latex</th></tr>
<tr><th>25 mm</th><th>Blast Furnace Slag</th></tr>
<tr><td rowspan="3">Blast Furnace Slag Aggregate 0%</td><td>78.82</td><td rowspan="18">305.88</td><td rowspan="3">1411.76</td><td rowspan="3">-</td><td>-</td><td>-</td></tr>
<tr><td>78.82</td><td>1.41</td><td>-</td></tr>
<tr><td>75.29</td><td>-</td><td>6.12</td></tr>
<tr><td rowspan="3">Blast Furnace Slag Aggregate 20%</td><td>78.82</td><td rowspan="3">1129.41</td><td rowspan="3">282.35</td><td>-</td><td>-</td></tr>
<tr><td>78.82</td><td>1.41</td><td>-</td></tr>
<tr><td>75.29</td><td>-</td><td>6.12</td></tr>
<tr><td rowspan="3">Blast Furnace Slag Aggregate 40%</td><td>78.82</td><td rowspan="3">847.06</td><td rowspan="3">564.71</td><td>-</td><td>-</td></tr>
<tr><td>78.82</td><td>1.41</td><td>-</td></tr>
<tr><td>75.29</td><td>-</td><td>6.12</td></tr>
<tr><td rowspan="3">Blast Furnace Slag Aggregate 60%</td><td>78.82</td><td rowspan="3">564.71</td><td rowspan="3">847.06</td><td>-</td><td>-</td></tr>
<tr><td>78.82</td><td>1.41</td><td>-</td></tr>
<tr><td>75.29</td><td>-</td><td>6.12</td></tr>
<tr><td rowspan="3">Blast Furnace Slag Aggregate 80%</td><td>78.82</td><td rowspan="3">282.35</td><td rowspan="3">1129.41</td><td>-</td><td>-</td></tr>
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<tr><td rowspan="3">Blast Furnace Slag Aggregate 100%</td><td>78.82</td><td rowspan="3">-</td><td rowspan="3">1411.76</td><td>-</td><td>-</td></tr>
<tr><td>78.82</td><td>1.41</td><td>-</td></tr>
<tr><td>75.29</td><td>-</td><td>6.12</td></tr>
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2.3. Test Methods

2.3.1. Void Ratio

Porous vegetation concrete has voids to enable plant growth, and the void ratio is an important characteristic of this concrete. If the void ratio is too small, the strength will be increased, but plant growth will not be encouraged, whereas if the void ratio is too high, there will be problems due to decreased concrete strength. Thus, an appropriate void ratio is important. We analyzed the influence of different blast furnace slag aggregate amounts and assessed whether adding natural jute fiber and latex affected the void ratio. The void ratio test was carried out with a cylinder-shaped test structure (100-mm in diameter and 200-mm high), according to the volume used in the "Porous Concrete Void Ratio Test Method" of the Eco Concrete Study Committee of the Japanese Concrete Industry Association. The ratio was calculated using Equation (1) at an age of 28 days.

$$P_a = 1 - \frac{W_2 - W_1}{V} \text{ x } 100 \quad (1)$$

where W_1 and W_2 are the underwater and air-dried weights of the specimen, respectively, and V is the volume of the specimen.

The void ratio measurement was carried out on the test specimens after initial curing at 23 ± 2 °C for 24 h (relative humidity ~58%), and underwater curing for 27 days in a 23 ± 2 °C curing chamber. The void amount of the porous vegetation concrete was measured after drying the underwater-cured test specimens in a 105 ± 5 °C oven for 24 h to achieve an absolute dry state.

2.3.2. Compressive Strength

Porous vegetation concrete has a relatively large void ratio, which can degrade its compressive strength significantly. However, in the case of material for which the main purpose is to encourage vegetation, it is sometimes more important to improve the void ratio rather than the strength when the goal is ecosystem restoration. However, in the case of a vegetation concrete block used for river/shore protection, both stability and plant growth have to be ensured, so some tradeoff is necessary. In this study, we assessed the effects of blast furnace slag aggregate in different amounts, as well as the impact of adding natural jute fiber and latex. Reinforcing fiber may increase the amount of bonding material in the interface between aggregates, which is a major reason for the destruction of porous vegetation concrete blocks. Increasing strength via interface reinforcement may be possible, and latex could increase the adhesive power of the material, thereby improving resistance against destruction; also, due to the characteristics of the dry manufacturing method, the water/cement ratio may be low, which could improve formability and reduce the strength decrease caused by adhesive power degradation (in turn due to insufficient coating of the aggregate surface bonding material). To analyze the compressive strength of the porous vegetation concrete, compressive strength tests were conducted according to ASTM C39/C39M-15a [21]. The experiment was carried out with initial curing at 23 ± 2 °C for 24 h (relative humidity ~58%) on test specimens 100-mm in diameter and 200-mm high, and 27 days underwater curing in a 23 ± 2 °C curing chamber.

2.3.3. CO_2 Emissions Analysis

The production stage of general purpose concrete is divided into three stages: materials, transportation, and manufacturing stages [15,16]. In existing studies, CO_2 emissions are analyzed during each stage (Figure 2). In this study, CO_2 emissions were analyzed only in the materials and transportation stages. According to past studies, the amount of CO_2 emissions released during the concrete manufacturing stage is very small (as low as 0.2%), so it is excluded here. The CO_2 emissions of the porous vegetation concrete were analyzed when mixing 1 m^3 of the material as a standard.

In the materials stage, CO_2 emissions generated during the production of cement, aggregate, fiber, and latex, which represent the raw materials required to manufacture the porous vegetation concrete, were calculated based on CO_2 units for each material. The CO_2 emissions at the material stage were calculated by Equation (2) [15,16].

$$Em = \sum(EM \times a) \quad (2)$$

Here, Em is the total CO_2 emissions (kg·CO_2/m^3) in the material stage, EM is the amount (kg) of each component material in the 1 m^3 porous vegetation concrete mix, and a is the CO_2 emissions from each material (kg·CO_2/kg).

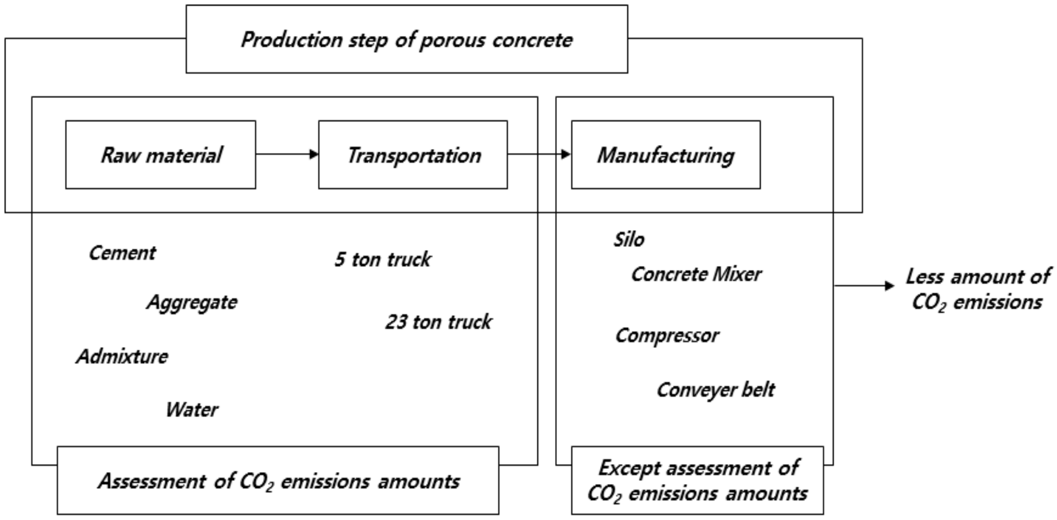

Figure 2. Porous vegetation concrete production stage and CO_2 emission analysis item.

CO_2 emissions for each raw material are listed in Table 6 [22]. The amount of CO_2 emitted from Portland cement production represents the total CO_2 emissions at all stages in the cement production process. In the case of blast furnace slag aggregate, a domestic CO_2 emissions amount has not been established, so the recycled aggregate's CO_2 emissions amount was used instead. The production of recycled aggregate is divided into production, transportation, and dismantling processes, but the CO_2 emissions during production (~49%) and dismantling (50%) account for 99% or more of the total emissions. In the case of blast furnace slag aggregate production, there is no dismantling process, so the CO_2 emissions were assumed to be 49% of the recycled aggregate's CO_2 emissions. Styrene butadiene rubber is the main ingredient in latex, and the latex in vegetation concrete is 50% solid; thus, we used 50% of styrene butadiene rubber's CO_2 emissions.

Table 6. CO_2 emission amounts of materials [22].

Material	CO_2 Emission Amounts
Portland cement	0.944
Blast furnace slag cement	0.208
Coarse aggregate	0.0075
Recycled aggregate	0.0149
Styrene butadiene rubber	2.49
Water	0.000332

For the transportation stage, energy consumption according to the distances over which materials must be transported for porous vegetation concrete production were calculated for the CO_2 emissions analysis. The energy consumption and CO_2 emissions for transportation vehicles are shown in Table 7, and each material's transportation stage CO_2 emissions were calculated with Equation (3) [15,16].

$$Et = \left(\frac{Ts}{Lt}\right) \times ds \times b \quad (3)$$

Here, E_t is the total CO_2 emissions ($kg{\cdot}CO_2$) for the transportation stage, *Ts* is the amount of water (tons) required to produce 1 m^3 of porous vegetation concrete, *Lt* is the transportation equipment's capacity (tons), *ds* is the transportation distance (km), and *b* is the transportation equipment's CO_2 emissions ($kg{\cdot}CO_2$/ton·km).

For each material, the transportation distances and vehicles used in the transportation stage CO_2 emissions calculation are shown in Table 7. To produce porous vegetation concrete, if the raw material production site is 50 km away or further, economic feasibility will not be achieved, so the cement and crushed aggregate were assumed to be 50 km away. The other raw materials cannot be brought from shorter distances, so actual distances (slag and fiber is 100 km, latex is 200 km) were estimated.

Table 7. The energy consumption and CO_2 emissions for transportation vehicles.

Transport Vehicles			Materials		
Transport Facility	**Energy Consumption (MJ/ton·km)**	**CO_2 Emission ($kg{\cdot}CO_2$/ton·km)**	**Type of Material**	**Transport Distance**	**Transport Facility**
1-ton truck	0.089	0.268	Portland cement	50 km	23-ton truck
2.5-ton truck	0.048	0.146	Slag cement	50 km	23-ton truck
5-ton truck	0.033	0.092	Coarse aggregate	50 km	23-ton truck
8-ton truck	0.021	0.098	Slag aggregate	100 km	23-ton truck
18-ton truck	0.017	0.063	Fiber	100 km	1-ton truck
23-ton truck	0.15	0.051	SB Latex	200 km	5-ton truck

3. Results and Discussion

3.1. Analysis of CO_2 Emissions by Production Stage

CO_2 emissions for each raw material were analyzed by assuming the maximum usage of the material in question. The results are shown in Figure 3. CO_2 emissions for the included materials were highest for cement, followed by aggregate, SB latex, and fiber. When using blast furnace slag aggregate, there was a 30% or more CO_2 emissions-reducing effect compared with using general crushed aggregate. The production of latex showed the highest CO_2 emissions, but the quantity used in concrete is much less in comparison to cement and aggregate, so emissions per 1 m^3 of concrete were low. Also, the fiber has a very low CO_2 emission compared to other materials. In this experiment, Portland cement was not used, but the CO_2 emissions data for Portland cement were included; when blast furnace slag cement was used, CO_2 emissions were reduced by ~78% versus Portland cement. In the future, the use of furnace slag cement in general purpose concrete would have a significant CO_2 emissions-reducing effect.

An analysis of CO_2 emissions for the raw materials in the transportation stage is shown in Figure 4. The highest CO_2 emissions were associated with the aggregate. It can be seen that this is important because of the large amount of aggregate in concrete. In the case of blast furnace slag aggregate, the transportation distance was greater, resulting in high CO_2 emissions. The next-highest CO_2 emitter was fiber; this was the result of a greater transportation distance and the use of a 1-ton truck, because of the smaller quantity of material. CO_2 emissions at each production stage are shown in Figure 5. A high amount of CO_2 was generated in the materials and transportation stages. For fiber, ~12% of the CO_2 emissions were attributable to transport.

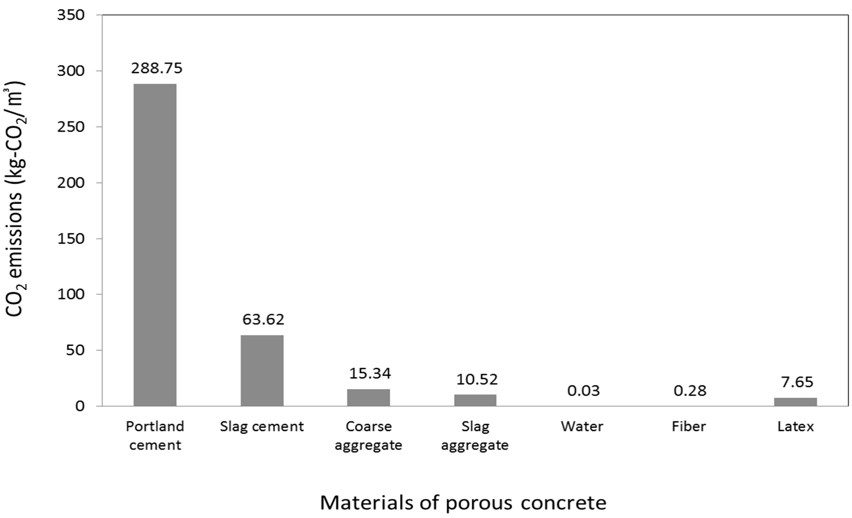

Figure 3. CO_2 emissions of materials stage.

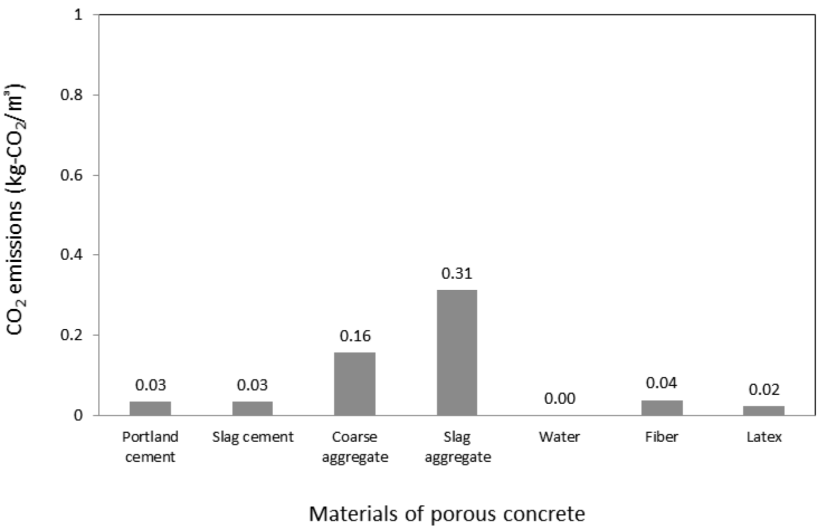

Figure 4. CO_2 emissions of transportation stage.

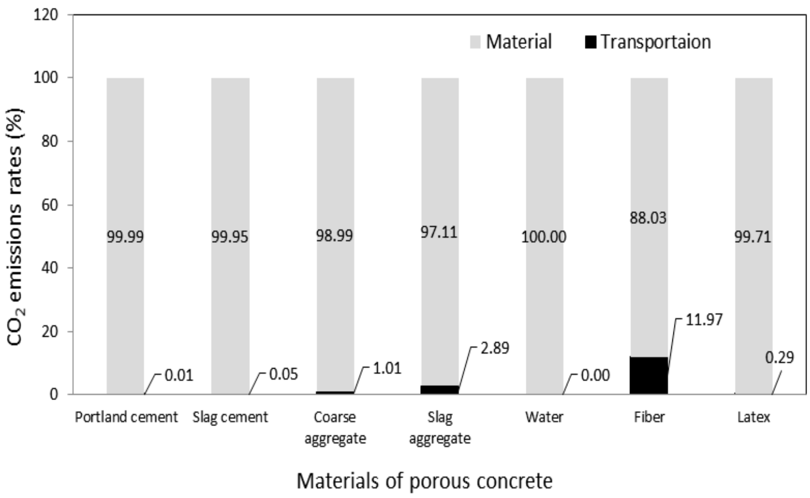

Figure 5. CO_2 emissions by production stage.

3.2. Analysis of Void Ratio, Compressive Strength, and CO_2 Emissions-Reducing Effects

This study assessed the ability of reinforcing fiber and SB latex to improve the performance of porous vegetation concrete and blast furnace slag aggregate, in terms of achieving a CO_2 emissions-reducing effect. The relationship between void ratio and CO_2 emissions is shown in Figure 6. According to the void ratio test results, the void ratio increased when natural jute fiber was added. The void ratio also increased when latex was added, but showed a smaller increase compared to when jute fiber was added. Blast furnace slag aggregate replacement at ratios of 20% and 40% showed the biggest effect on the void ratio. The relationship between void ratio and CO_2 emissions generally showed decreased CO_2 emissions as the void ratio decreased. This is because the void ratio decreased as more blast furnace slag aggregate was used in this case, and CO_2 emissions showed a similar decrease.

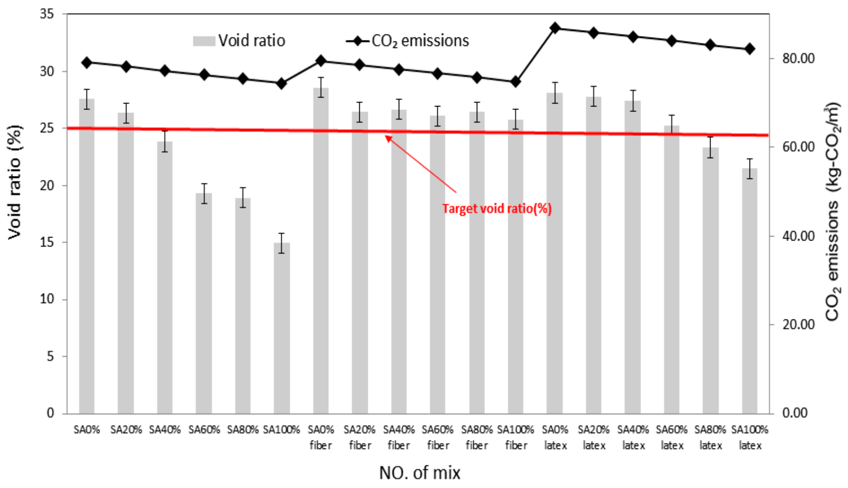

Figure 6. Analysis of void ratio and CO_2 reduction effect.

The change in void ratio caused by adding reinforcing fiber and latex is shown in Figure 7. In the control mix, with the addition of latex, the void ratio showed an increase up to 20% of blast furnace slag, but the void ratio declined above that threshold. In all fiber reinforcing mixes, a void ratio-degrading effect was seen. The void ratio decreased by a maximum of 45.7% in control mixes; in jute fiber mixes, it decreased by a maximum of 6.49% and, when latex was added, it decreased by a maximum of 22.28%.

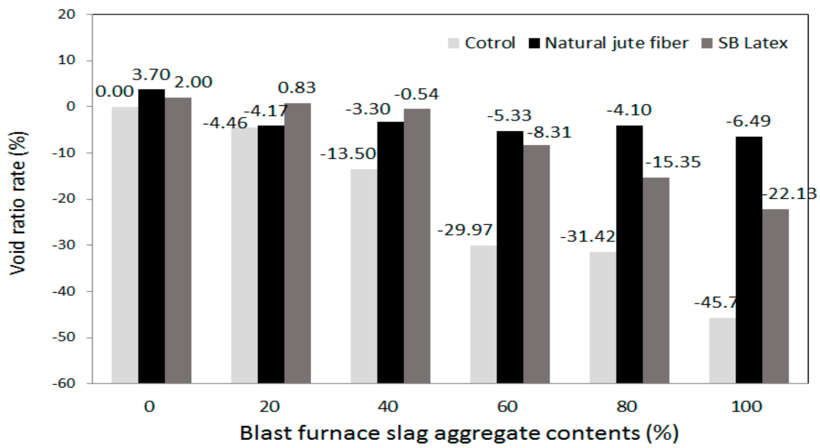

Figure 7. Void ratio increasing rate according to blast furnace slag replacement rate.

The effects of the mixes on the porous vegetation concrete's compressive strength and CO_2 emissions are shown in Figure 8. The use of latex increased the porous vegetation concrete's compressive strength. This is because latex increases initial liquidity, allowing smooth bonding material to coat the aggregate and thus increase the adhesive strength between aggregates. The addition of reinforcing fiber resulted in decreased compressive strength; the porous vegetation concrete mixes were dry during manufacturing, with a very small slump. There was insufficient liquidity and this influenced the decrease in strength. Thus, when using fiber reinforcing, it is also important to apply a method to increase initial liquidity. As the amount of blast furnace slag aggregate increased, there was a tendency for decreased compressive strength, likely because blast furnace slag aggregate has many voids.

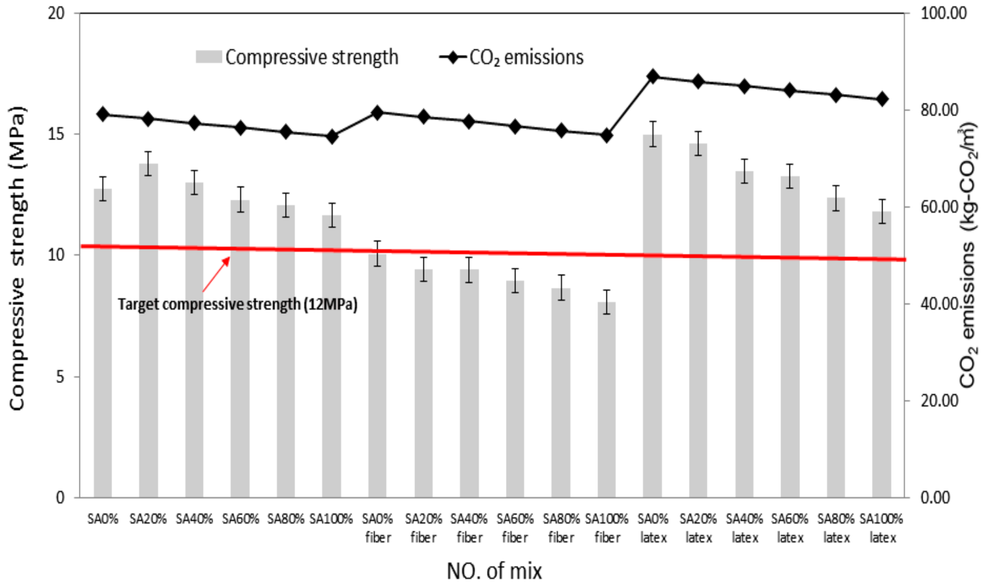

Figure 8. Relationship between amounts of CO_2 emission and compressive strength.

The CO_2 emissions analysis showed a CO_2 emissions-reducing effect as the blast furnace slag aggregate amount increased. The use of latex increased CO_2 emissions whereas the use of reinforcing fiber had little influence on emissions.

The compressive strength increased in mixes using reinforcing fiber and latex, as shown in Figure 9. In the control mixes, the strength increased with blast furnace slag up to 40%, but degraded strength occurred above that threshold. In the mixes that used fiber reinforcing, 20%–37% strength decreases were seen. In mixes that included latex, strength degradation occurred when the blast furnace slag aggregate replacement ratio was 80% or more, whereas with the use of latex, the strength increase was 4%–18%.

The CO_2 emissions were increased in mixes using reinforcing fiber and latex, as shown in Figure 10. As the amount of blast furnace slag aggregate increased, there was a decrease in CO_2 emissions. In all control mixes, and in those with fiber reinforcing, the effect was a CO_2 emissions decrease of 1%–6%. The use of latex caused CO_2 emissions to increase by at least 3%–10%. Thus, although latex increased the strength, it also increased the CO_2 emissions. However, if 100% blast furnace slag aggregate was used, this reduced the CO_2 emission amounts by about 6%.

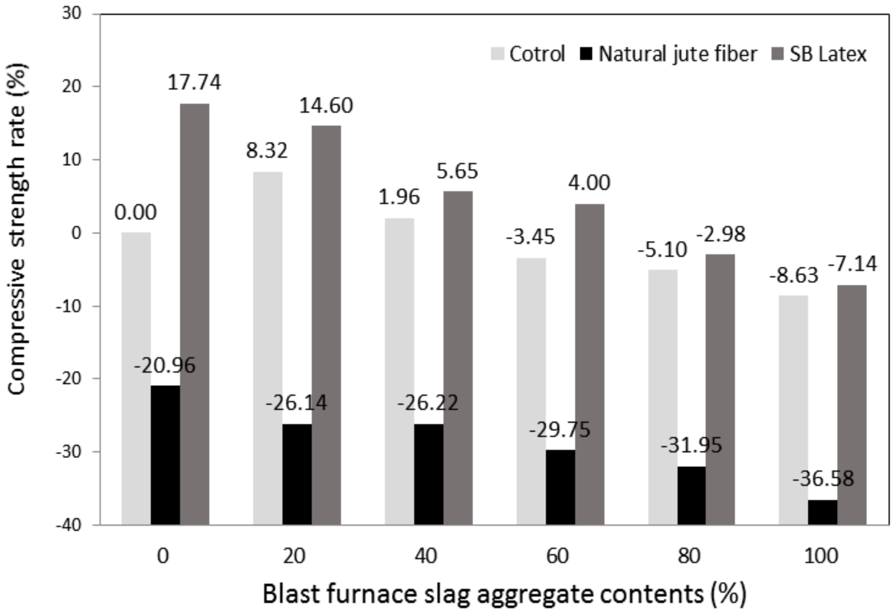

Figure 9. Increase rate in compressive strength according to use of fiber reinforcement and latex.

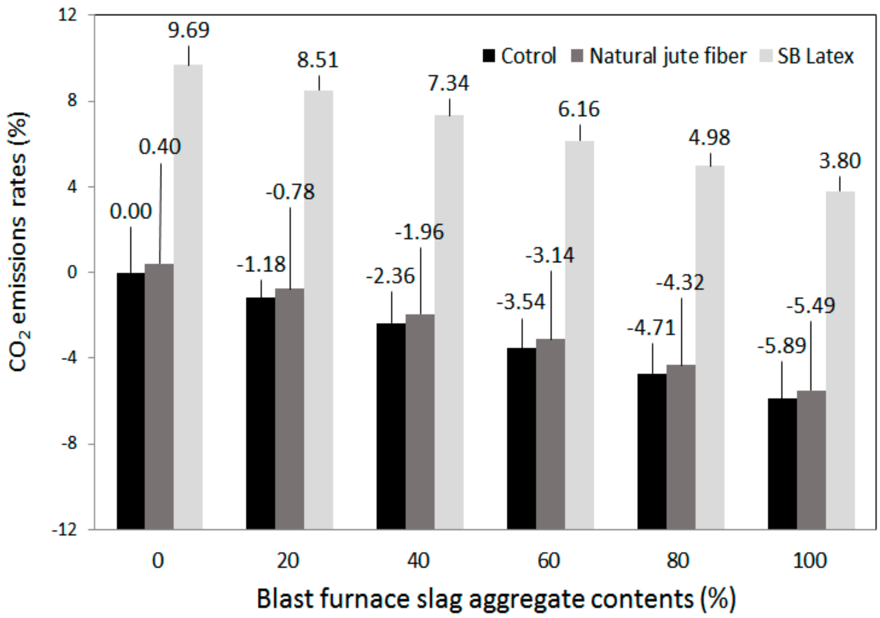

Figure 10. Increasing rate in CO_2 emissions from fiber reinforcement and latex use.

4. Conclusions

In this study, the influence of fiber reinforcing, SB latex, and blast furnace slag aggregate use was analyzed with respect to porous vegetation concrete's compressive strength and CO_2 emissions. A summary of the key results now follows.

1. A void ratio analysis of porous vegetation concrete that used reinforcing fiber and latex showed that, as the replacement ratio of blast furnace slag aggregate increased, the void ratio decreased. When natural jute fiber was added, the void ratio increased, whereas if latex was added, the void ratio increased, but to a lesser degree compared with the case of adding jute fiber.

2. In the analysis of the compressive strength of porous vegetation concrete that used reinforcing fiber and latex for increased strength, use of latex increased compressive strength, but reinforcing fiber caused strength degradation.

3. The use of blast furnace slag aggregate to reduce porous vegetation concrete's CO_2 emissions did decrease the emissions, but the compressive strength also decreased as the amount of blast furnace slag aggregate used increased.

4. CO_2 emissions of the raw materials were highest for cement, followed by aggregate, SB latex, and fiber. The blast furnace slag aggregate showed a 30% or more CO_2 emissions-reducing effect versus crushed aggregate, and the use of blast furnace slag cement resulted in a 78% CO_2 emissions-reducing effect versus Portland cement. In the future, significant CO_2 emissions-reducing effects could be achieved if these industrial by-products were used in general purpose concrete.

5. In a CO_2 emissions analysis of the transportation of raw materials, aggregate showed the highest CO_2 emissions, followed by fiber. This was the result of a greater transportation distance of a 1-ton truck that had high CO_2 emissions.

6. Regarding CO_2 emissions during production, the materials stage generated the most emissions, while emissions in the raw materials transportation stage were low (below 3% of total emissions), except for fiber.

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