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An Environmental Assessment of Interlocking Concrete Blocks Mixed with Sugarcane Residues Produced in Okinawa

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Abstract: The use of sugarcane residues in mortar and concrete is believed to contribute to the reduction of environmental problems, such as the reduction of mining of natural aggregates as well as the improper disposal of sugarcane residues. Therefore, in this study, bagasse fiber and bagasse sand were added into the preparation of the interlocking concrete blocks, and the flexural strength and an environmental assessment of the blocks were analyzed. The flexural strength of the blocks was not affected by the addition of the bagasse fiber and bagasse sand. In addition, the environmental load of interlocking concrete blocks using sugarcane residues was lower than the blocks using conventional aggregates due to the greater simplicity of acquisition of the residues. Moreover, in the scenarios where the blocks are supposedly made on smaller islands, the emissions increased due to long-distance transportation, since conventional aggregates come from other islands.

Keywords: sugarcane bagasse fiber; sugarcane bagasse sand; flexural strength; interlocking concrete block; environmental assessment

1. Introduction

According to the Food and Agriculture Organization of the United Nations (FAO), sugarcane is produced in more than 100 countries in tropical and subtropical regions of the world [1], characterized by warm temperatures. Of the sugar manufactured around the world, 70% is from sugarcane [2]. Further, sugarcane has been used for the production of bioethanol in some countries, such as Brazil. However, during the manufacture of the sugar and ethanol, a high quantity of residues are generated. Among the residues, there is the bagasse [3], which is usually used as a primary fuel source in sugar/ethanol mills [3,4]. As a result, residual products composed of sand, ash [5–9], and unburned bagasse are generated from the boilers. The sugarcane residues are generated in large quantities and create a serious disposal problem for the sugar/ethanol industry, affecting the environment and public health [10]. In several countries, these residues have been mainly discarded as soil fertilizer. However, in view of the environmental impact, this method of disposal is far from being the most suitable one [11,12]. This is because the bagasse ash does not have adequate mineral nutrients. In addition, solubilization and leaching tests performed on bagasse ash samples indicated the presence of heavy metals [5].

On the other hand, according to Lizhen Huang [13], the total CO_2 emission of the global construction sector was 5.7 billion tons in 2009, contributing to 23% of the total CO_2 emissions produced by global economic activities. In addition, as cited by Bas J. et al. [14], the heavy industry sector, such as cement and steel production, is a major source of greenhouse gas emissions. The cement and steel industries together accounted for 8% of global energy use and 15% of global anthropogenic CO_2 emissions in 2012. The dependency of the construction sector on natural resources like sand and gravel is another issue. Exhaustive mining leads to problems such as vegetation loss, loss of water retaining strata, lowering of the groundwater table, and disturbance in the existing ecosystem. For these reasons, several regions adopted mining restrictions, which reduced the availability of good aggregates at shorter haul distances. As a consequence, the transportation of aggregates from longer distances to construction sites increased the cost, which increased the total cost of construction [15,16], as well as impacting the environment with CO_2 emissions due to long distance transportation.

Okinawa Prefecture is one of the 47 prefectures of Japan and is located in the southwest of Japan. Since Okinawa Prefecture consists of a series of small islands, the concrete aggregates are generally crushed stone and sea sand because of the lack of adequate river to obtain ordinary river aggregates [17]. In addition, the mining/collection of the aggregates is concentrated on the main island of Okinawa, where the capital city Naha is located. Therefore, the aggregates are transported from the main island of Okinawa to smaller islands by vessels. Figure 1 illustrates the prices per m^3 of the fine aggregates, which are available online and published monthly in a magazine [18,19], and the location of sugar factories in Okinawa Prefecture [20].

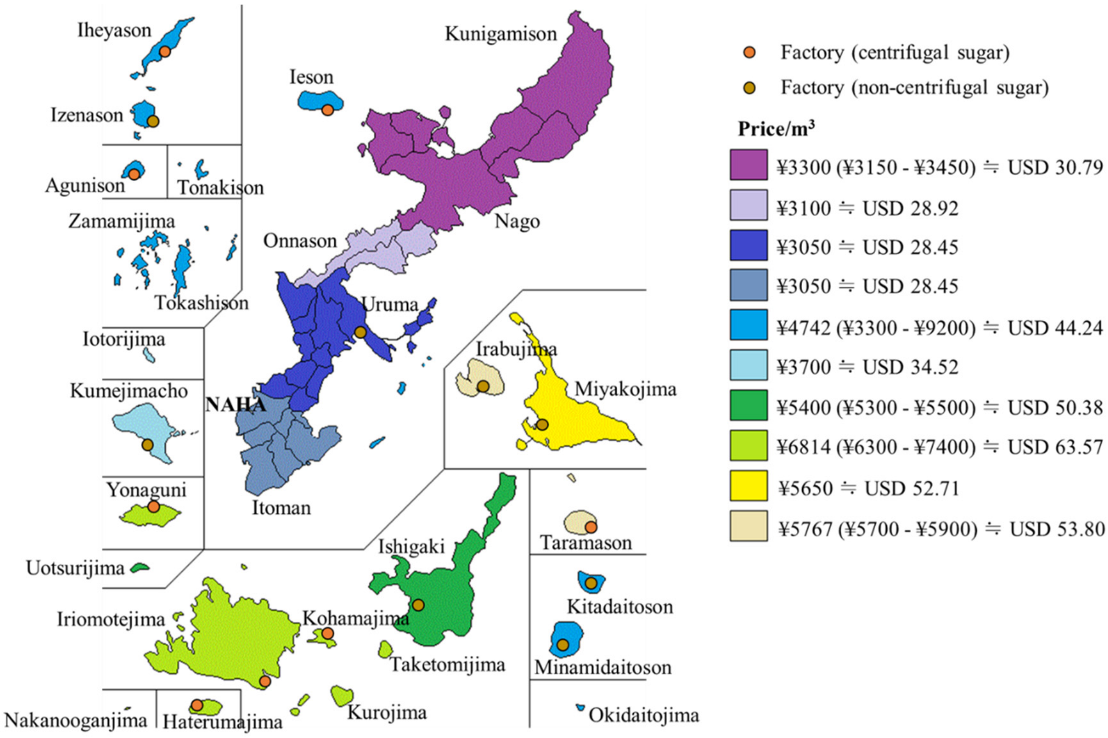

Figure 1. Price of the fine aggregates and location of sugar factories in Okinawa Prefecture.

The use of sugarcane residues as construction aggregates provides a more sustainable alternative for the construction industry and the sugar/ethanol industry [21]. The use of local sugarcane residues as aggregates for concrete, especially for islands with small land area, are desirable, since it can reduce environmental load and decrease transportation CO_2 emissions. In addition, the development of more construction material options is very important, since a country's policies may repeatedly change. Japan's government announced that it aims to reduce coal-fired power generation by about 90% by 2030 [22]. This can dramatically reduce fly ash production in all of Japan, and consequently, it may impact the use of fly ash as aggregates. Therefore, this study aims to assess the environmental impacts of the utilization of sugarcane residues as concrete aggregates in the production of interlocking concrete blocks.

2. Interlocking Concrete Blocks

2.1. Materials

The surface layer of all interlocking concrete blocks was made using white Portland cement (WPC) and quartz sand (QS). The base layer of all interlocking concrete blocks was made using ordinary Portland cement (C), coarse aggregate FM (Fineness Modulus): 5.00 (G), and fine aggregate FM: 3.05 (S). Note that tap water (W) and the chemical admixture (CA (MasterMatrix 200, 1.03–1.07 g/cm^3)) for immediate demolding products (air entrainment type) were used in both layers for the preparation of the interlocking concrete blocks.

Figure 2 shows a diagram of the aggregate production process using sugarcane residues. The sugarcane residues (raw bagasse and burned residues) were acquired from a sugar mill in Okinawa Prefecture, Japan. The raw bagasse was dipped in water at 30 °C for 30 min and then dried in the open air. The intent of this process was to reduce the residual sugar content of the bagasse and eliminate impurities [21,23–26]. Afterwards, the residues were classified by a sieving process. Raw bagasse that passed through a 9.52 mm sieve and remained in a 4.75 mm sieve was classified as bagasse fiber (BFL). The burned residues that passed through a 1.18 mm sieve and remained in a 0.297 mm sieve were classified as bagasse sand (BS). The physical properties of the materials are given in Table 1.

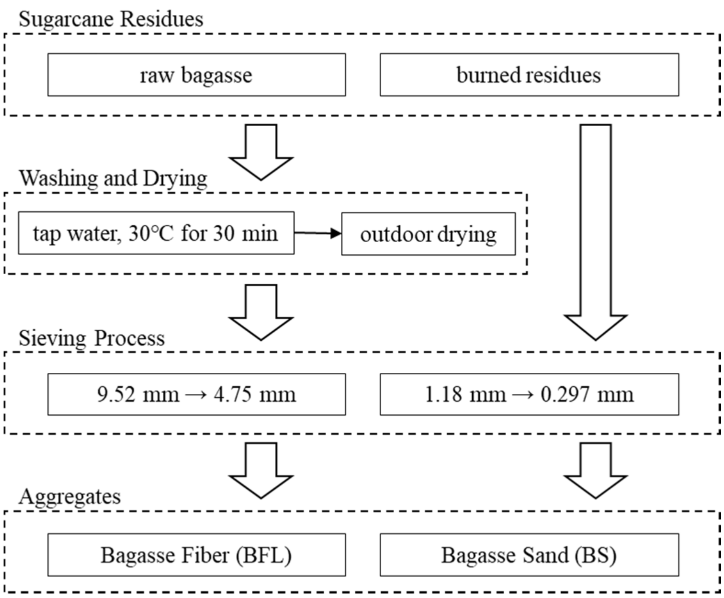

Figure 2. Diagram of aggregate production process.

Table 1. Physical properties of cement and aggregates.

Properties	**Materials**						
	Surface Layer		**Base Layer**				
	WPC	**QS**	**C**	**G**	**S**	**BFL**	**BS**
Density (g/cm^3)	3.05	2.60	3.16	2.68	2.68	0.49	1.29
Total alkali content (%)	0.1	—	0.56	—	—	—	—
Specific surface area (cm^2/g)	3440	—	3280	—	—	—	—
Loss on ignition (%)	2.79	—	2.26	—	—	—	—

2.2. Concrete Mixture

The mix proportions of the surface and the base layer of interlocking concrete blocks are shown in Table 2. The composite of the surface layer is the mixture with the water to cement ratio (*W/C*) of 0.25. Note that the surface layer mixture was the same for all blocks. In the case of the base layer, composite *C* is the mixture with *W/C* of 0.15. Composite *C* represents the standard interlocking concrete block and contains no sugarcane residue materials. The BFL2 block was prepared with bagasse fiber volume ratios of 2% in comparison to the total quantity of aggregates. Moreover, the interlocking concrete block using bagasse sand (BS) was prepared. In this case, the bagasse fiber volume ratio is 2% and the BS volume ratio is 5%, for a total of sugarcane residue ratio of 7% in comparison to the total quantity of aggregates. All residue materials were replaced in place of the aggregates in the same proportions.

Table 2. Mix proportions of the surface and base layers of specimens.

Layer	Composites	Residues Type	Residues (Vol. %)	w/c	Unit (kg/m^3)								
					WPC	QS	C	W	G	S	BFL	BS	CA
Surface	—	—	—	0.25	582.6	1721.7	—	145.6	—	—	—	—	1.2
Base	C	—	—	0.15	—	—	436.1	64.0	1068.0	1068.0	—	—	1.1
	BFL2	Bagasse Fiber	2		—	—			1046.6	1046.6	7.8	—	1.1
	BS	Bagasse Fiber	2		—	—			993.2	993.2	7.8	51.4	1.1
		Bagasse Sand	5		—	—							

2.3. Preparation of Blocks

The surface layer concrete was prepared using an oscillating type mixer (OM-70NB8). First, the cement and the quartz sand were placed into the mixer and dry mixed for 20 s at low speed (rotation speed: 120 ± 5 rpm). After that, the mixer speed was changed to high speed (rotation speed: 216 ± 5 rpm), and the dry mixing was continued for 30 s. Then, the water and admixture were placed into the mixer and mixed for 20 more seconds at low speed (rotation speed: 120 ± 5 rpm) and 50 s at high speed (rotation speed: 216 ± 5 rpm).

In the case of the base layer concrete, the cement and sand were placed into the mixer and dry mixed for 20 s at low speed (rotation speed: 120 ± 5 rpm) and for 30 more seconds at high speed (rotation speed: 216 ± 5 rpm). Later, the residues, water, and admixture were placed into the mixer and mixed for 30 more seconds at low speed (rotation speed: 120 ± 5 rpm) and 60 s at high speed (rotation speed: 216 ± 5 rpm). All mixtures were mixed in an oscillating type mixer (OM-350NB8).

The mixture of the base layer of interlocking concrete blocks was cast in a formwork of 98 × 198 × 60 mm, pressed (about 2682.5 kgf), and vibrated (50 Hz, 4000 rpm) for about 1 s. Right after, the mixture of the surface layer of interlocking concrete block specimens was cast on the base layer mixture in the formwork, pressed (about 3756.0 kgf), and vibrated (55 Hz, 4500 rpm) for 4 more seconds. Then, the specimens were de-molded, placed in a room, and cured for 1, 3, 5, 7, 10, 14, and 28 days. The outline of specimens is shown in Figure 3.

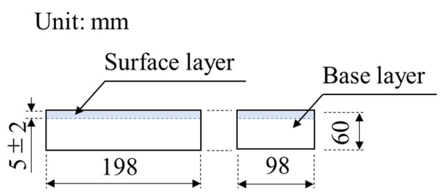

Figure 3. Outline of specimens.

2.4. Flexural Strength Test

A flexural strength test was performed on 3 blocks of each mixture in order to determine the flexural strength of the blocks according to JIS A 5371 at 28 days.

3. Environmental Assessment

3.1. Goal and Scope

The objective of this study was to make an environmental assessment comparison between interlocking blocks with sugarcane residues and conventional interlocking concrete blocks. However, except for aggregates where the proportions were modified (see Table 2), materials such as cement, water, and chemical admixtures were excluded from the scope of the research, as well as the mixing process that was carried out under the same conditions for all mixtures. The scope of recycling interlocking concrete blocks removed after the end of their useful life as pavement was also excluded from the analysis. Usually, the main destination of recycled mortar and concrete is the construction of pavement [27]. In this study, it was assumed that the interlocking blocks used here will have no problems and can be recycled into pavement materials.

Based on the above, the study has focused only on the parts of sugarcane residues and conventional aggregates and has set the scope of the investigation to the raw materials, manufacturing, and transportation processes.

3.2. System Boundaries of Scenarios

Three scenarios were considered on the main island of Okinawa Figure 4 the system boundaries on the main island of Okinawa.

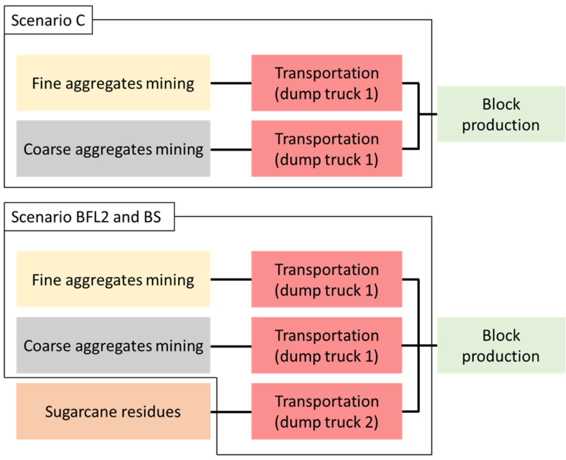

Figure 4. System boundaries on the main island of Okinawa.

As seen in Figure 4, scenario C considers the environmental assessment of the conventional interlocking concrete blocks in which sugarcane residues were not used. Scenario BFL2 and BS consider the environmental assessment of the interlocking concrete blocks with the addition of sugarcane residues. The mix proportion of the blocks used in each scenario is shown in Table 2.

In addition, similar scenarios were applied on two other islands: Minamidaito and Yonaguni. In these cases, the means of transport change, resulting in a more complex way of transportation. Figures 5 and 6 show the system boundaries in the cases of Minamidaito and Yonaguni, respectively. Note that in the scenarios of Minamidaito and Yonaguni, it was assumed that the blocks were prepared near the main port of each island in order to avoid the use of other transportation. In addition, the sugarcane residues are produced on the same island where the interlocking concrete blocks were supposedly produced (see Figure 1); therefore, the residues do not need vessel transportation.

The environmental load in all scenarios in both aggregate mining/collection and transportation processes was calculated. However, since the bagasse residues are waste, the process of mining/collection was not considered. The functional unit of the assessment assumes 1000 L of concrete.

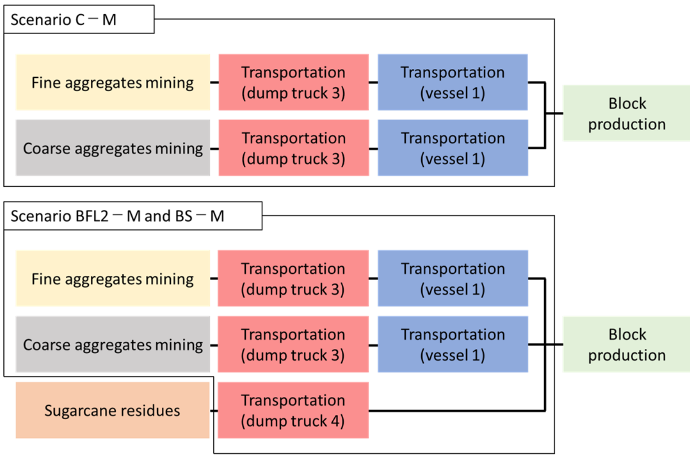

Figure 5. System boundaries on Minamidaito.

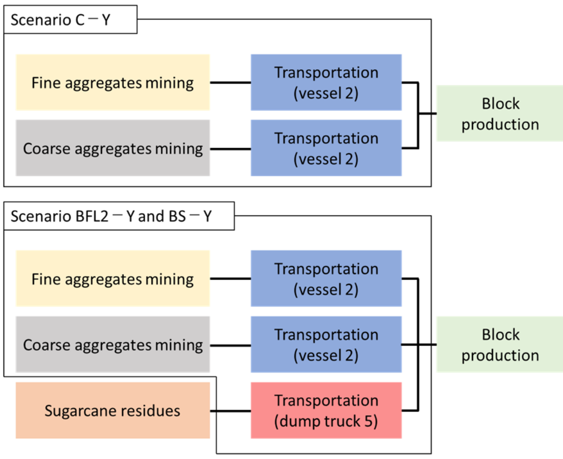

Figure 6. System boundaries on Yonaguni.

3.3. Inventory

The environmental assessment analysis includes emissions associated with aggregate manufacturing and transportation. The environmental load associated with aggregate manufacturing and transportation is shown in Table 3. The truck and vessel assumed for the transportation of the aggregates, including the residue materials, were a 10 ton dump truck with a diesel engine and a 500 ton capacity vessel.

Table 3. Environmental load associated with aggregate manufacturing and transportation [28,29].

	Unit (*)	Carbon Dioxide ($kg\text{-}CO_2/*$)	Sulfur Oxide (kg-SOx/*)	Nitrogen Oxide (kg-NOx/*)	Dust and Soot (kg-PM/*)
Fine aggregate	kg/t	3.7	0.00860	0.00586	0.00199
Coarse aggregate	kg/t	2.9	0.00607	0.00415	0.00141
Dump truck	km·t	0.117	0.0000901	0.000875	0.0000735
Vessel	km·t	0.162	0.00280	0.00470	0.0000721

The equation used to calculate the total environmental load is as follows:

$$EL = \sum_{M_E}[(A_S \times E_S) + (A_G \times E_G)] + \sum_{T_E}[(T_S \times E_t) + (T_G \times E_t) + (T_R \times E_t)] \quad (1)$$

where EL: total environment load (kg); M_E: sum of emissions by aggregate (kg); T_E: sum of emissions by aggregate transport (kg); A_S: amount of fine aggregate (kg); E_S: emissions by fine aggregate (kg/ton); A_G: amount of coarse aggregate (kg); E_G: emissions by coarse aggregate (kg/ton); T_S: transport distance of fine aggregate (km); T_G: transport distance of coarse aggregate (km); T_R: transport distance of sugarcane residues (km); and E_t: emissions by transport (kg/(km·ton)).

The distance from the mining/collection place of the aggregates and residues to the plant where the interlocking concrete blocks were prepared is shown in Table 4.

Table 4. Distance from mining/collection place to plant.

Scenario	Transportation	Route	Distance (km)	
		From/To	Fine and Coarse Aggregate	Residues
Main Island	dump truck 1	Motobu/Uruma	51.4	—
	dump truck 2	Uruma/Uruma	—	9.5
Minamidaito	dump truck 3	Motobu/Naha	85.7	—
	dump truck 4	Minamidaito/Minamidaito	—	5.5
	vessel 1	Naha/Minamidaito	388	—
Yonaguni	dump truck 5	Yonaguni/Yonaguni	—	6.0
	vessel 2	Ishigaki/Yonaguni	131	—

4. Results and Discussion

4.1. Flexural Strength Test

Figure 7 shows the results of the flexural strength test after 28 days of curing. According to JIS A 5371, the interlocking concrete blocks with a flexural strength above or equal to 3 N/mm^2 could be used as pavement for pedestrians restricted to light vehicle traffic. When the flexural strength is above or equal to 5 N/mm^2, the restriction is extended to heavy vehicle traffic.

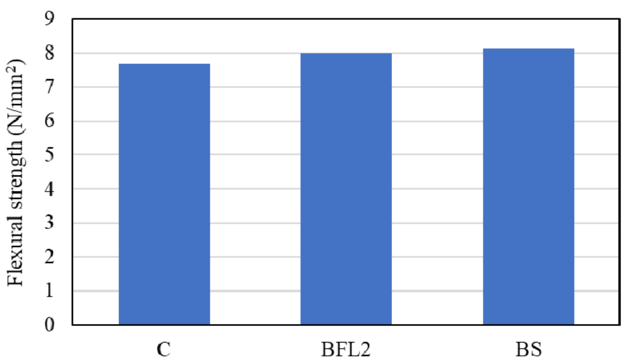

Figure 7. Flexural strength of each mixture.

As can be seen in Figure 7, the flexural strength was 7.80, 7.60, and 7.96 N/mm^2 for C, BFL2, and BS, respectively. From these results, it can be said that the addition of sugarcane residues in the interlocking concrete blocks does not negatively affect the strength of the blocks.

4.2. Environmental Load Associated With Production of Interlocking Concrete Blocks

Figures 8–11 show the amount of carbon dioxide, sulfur oxide, nitrogen oxide, and dust and soot emissions, respectively.

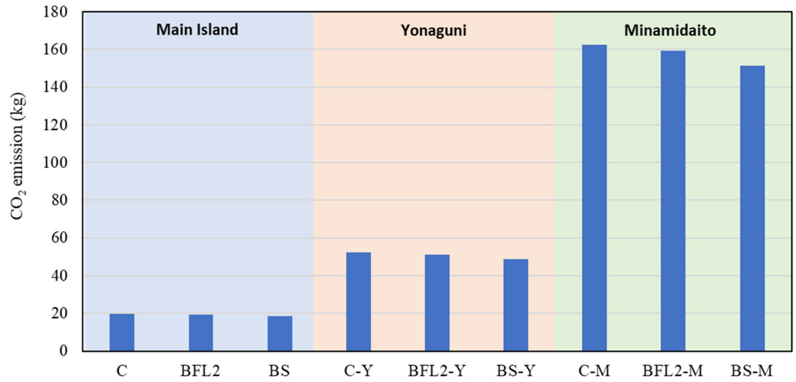

Figure 8. Carbon dioxide emissions.

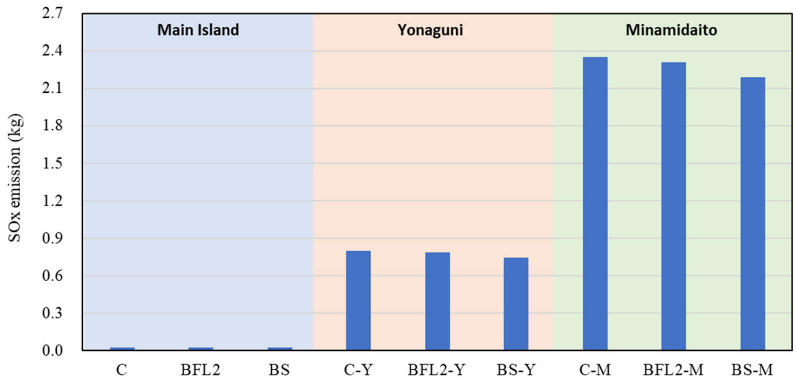

Figure 9. Sulfur oxide emissions.

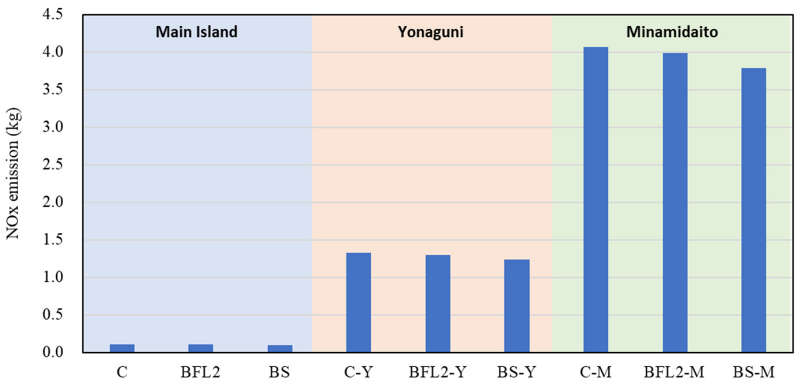

Figure 10. Nitrogen oxide emissions.

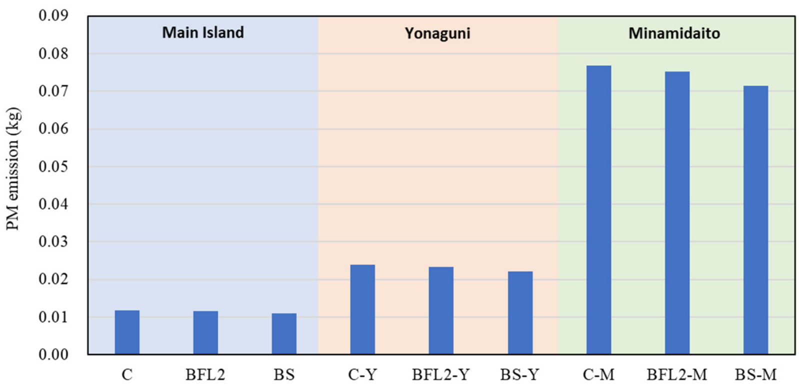

Figure 11. Dust and soot emissions.

As Figures 8–11 illustrate, the application of sugarcane residues can decrease the discharge of high-environmental-load substances into the air, water, and soil. A determining factor in the impact of concrete with sugarcane residues is the lower use of natural aggregates, which decrease the impacts from their extraction. In the BFL2 scenario, the percentage of decrease of the substances was around 1.96%, 1.97%, 1.94%, and 1.95%, while in the BS scenario, in which the volume of the residues used in the mixture was 7%, it was around 6.67%, 6.80%, 6.54%, and 6.65% in comparison to the C scenario for carbon dioxide, sulfur oxide, nitrogen oxide, and dust and soot emissions, respectively.

In the cases where the blocks are supposed to be made on the islands of Yonaguni and Minamidaito, the carbon dioxide, sulfur oxide, nitrogen oxide, and dust and soot emissions increase due to the long-distance transportation, since the conventional aggregates come from other islands. However, in the scenarios in which the sugarcane residues were added into the mixture, the emissions were smaller than the standard interlocking concrete block. In the case of BFL2-Y, the percentage of decrease of the substances was around 1.99%, 2.00%, 2.00%, and 1.99%, while in the case of BS-Y it was 6.92, 7.00, 6.98, and 6.89 in comparison to the C-Y scenario; in the case of BFL2-M, the percentage of decrease of the substances was around 2.00%, 2.00%, 2.00%, and 2.00%, while in the case of BS-M it was 6.98, 7.00, 6.99, and 6.97 in comparison to the C-M scenario for carbon dioxide, sulfur oxide, nitrogen oxide, and dust and soot emissions, respectively. These results are similar to the results obtained on the main island of Okinawa. However, the proportions of the environmental load were smaller than in the case of the main island, due to the need to transport the aggregates by vessels from other islands. In the case of Yonaguni, the aggregates are transported by vessels from the island of Ishigaki, which is located around 131 km from Yonaguni, and in the case of Minamidaito, the distance is around 388 km from the main island, where the aggregates were collected.

Although the environmental assessment analyses were performed in a simple way, the results point to a consistent environmental benefit resulting from the replacement of conventional aggregates with sugarcane residues. This contribution of the decrease of the environment load may be greater if the sugarcane residues are set to replace the fine aggregates only. In addition, if we consider that sugarcane can sequestrate up to 0.66 tons of CO_2 per ha per year [30], and even that a part of the bagasse is burned at the mill as fuel and generates CO_2, the carbon in sugarcane fiber came from CO_2 that was already present in the atmosphere [31], and the addition of these residues in the preparation of interlocking blocks may be considered highly eco-friendly. Accordingly, the optimization of the concrete mixture and strength of interlocking blocks should be investigated in detail in order to decrease the dependency of conventional aggregates from other islands and, consequently, the environmental load.

4.3. Cost Analysis Associated With Production of Interlocking Concrete Blocks

In addition, an easy cost analysis was carried out by setting the price for CO_2 reduction credits at ¥4500 (USD 59.71)/t·CO_2 [32]. In the case of BFL2 and BS scenarios, on the main island, the concrete cost decreases to around ¥2 (USD 0.02) and ¥6 (USD 0.06), respectively, in comparison to C. In the case of Yonaguni, the concrete cost decreases to around ¥5 (USD 0.05) and ¥16 (USD 0.15) for BFL2-Y and BS-Y, respectively, in comparison with C-Y. In the last case, in Minamidaito, the concrete cost of BFL2-M and BS-M decreases in comparison to C-M to around ¥15 (USD 0.14) and ¥51 (USD 0.48), respectively. These values reinforce that the use of local agro-residues, such as sugarcane residues, can favor the reduction of construction costs. However, some precautions must be taken so that these residues do not undergo various production processes, since this may increase the production costs of the residues as aggregates.

5. Conclusions

The environmental load associated with the production of interlocking concrete blocks using sugarcane residues as aggregates was found to be smaller than that of using conventional aggregates, largely due to the greater simplicity of acquisition of the residues. In the scenarios where the blocks are supposed made on the islands of Yonaguni and Minamidaito, the carbon dioxide, sulfur oxide, nitrogen oxide, and dust and soot emissions increase due to long distance transportation, since the conventional aggregates come from other islands.

In addition, the flexural strength for interlocking concrete blocks prepared with no sugarcane residues, blocks prepared with bagasse fiber volume ratios of 2% in comparison to the total quantity of aggregates, and blocks prepared with bagasse fiber volume ratio as 2% and bagasse sand volume ratio as 5% in comparison to the total quantity of aggregates, was 7.80, 7.60, and 7.96 N/mm^2, respectively.

6. Future Plans

This study has to be supplemented by additional experiments on interlocking concrete blocks containing higher fiber content. In addition, special attention should be given to the durability, since the behavior of organic matter, such as bagasse fiber, in concrete is still poorly understood.

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