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COMPARATIVE ANALYSIS OF THREE EMBANKMENT METHODS FOR ROAD CONSTRUCTION BY LIFE CYCLE ASSESSMENT AND COST

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ABSTRACT: In recent years, new composite geomaterials have been developed to reduce the weight of road construction materials in soft ground and mountainous areas in Japan that are prone to ground liquefaction and landslide. These new composite geomaterials have some problems, such as increased construction time, cost, and adverse impacts on the environment. As a result, conventional geomaterials are usually chosen over composite geomaterials in Japan. However, there are few researches that analyzed the environmental impacts (for example, CO_2, NOx, and SOx emissions as well as total life-cycle cost) of traditional and composite geomaterials quantitatively from the perspective of LCA (life cycle assessment). Therefore, the purpose of this research is to apply a LCA to estimate the total emissions of CO_2, NOx, and SOx as well as the total life cycle costs of three embankments—one constructed by the conventional method (cut and fill), one with lightweight geomaterial mixed with expanded polystyrene beads, and one by the expanded polystyrol construction method. All three embankments are located on a mountain road in Japan.

Keywords: Life Cycle Assessment, Life Cycle Cost, Air Pollutions, Lightweight Geomaterial Method, Expanded Polystyrol

1. INTRODUCTION

In Japan, many wetlands, rivers and coastal areas have been reclaimed to increase agricultural land, because the flat plains are narrow and limited. Therefore, there are many areas of potential ground settlement and liquefaction. In addition, since it is difficult to acquire land to construct roads in Japan, a lot of roads and some buildings have been built in the mountains, where there is potential for landslide. Against this background, new lighter composite geomaterials have recently been developed in Japan for application in soft ground and mountainous areas. Because of their lighter weight, these composite geomaterials are expected to help reduce liquefaction and landslide. Some researches pointed out that composite geomaterials leads to environmental load reduction by using construction generated soil as base material while there are different mechanical characteristics from normal geomaterials [1]-[2]. Therefore, many existing researches concerning composite geomaterials have clarified the mechanical characteristics and environmental load reduction are small [3]-[6].

In addition, other existing research describes various composite geomaterials and methods that have specific benefits and physical properties (e.g., cement-stabilized soil, lightweight treated soil treated with air foam, tire tip mixed soil, and the liquefied soil stabilization method), and estimates the amount of CO_2 emissions for each during manufacturing [7]–[8]. In addition, eco-efficiency assessments have been carried out through simulation and sensitivity analysis, as has an environmental assessment of composite geomaterials using construction sludge [9]. However, these existing researches has not compared newly developed composite geomaterials with the conventional method and estimated the emission of air pollutants for the entire life cycle throughout raw materials acquisition, construction, use and waste.

Therefore, the purpose of this research is to estimate the total emissions of CO_2, NOx and SOx as well as the total life cycle cost of three kinds of embankments—one constructed by the conventional method (cut and fill), one with lightweight geomaterial mixed with expanded polystyrene beads (LWGME) and one using the expanded polystyrol construction method. All three embankments are applied on a mountain road in Japan.

For the life cycle assessment (LCA) in this research, the estimates of the amount of air pollutants and CO_2 emissions generated by the three construction methods include the entire life cycle, from raw materials acquisition through construction, use, and waste. In addition, the total life cycle costs of these construction methods were calculated, and a comparative evaluation is included in this study.

2. METHOD AND SYSTEM DETAILS

The Mineoka area, located in the southern part of Japan's Chiba prefecture, was selected as a case study area for this research because landside control works are conducted on mountainous roads in the area (Fig. 1). We then established a functional unit to provide a logical basis for comparing the environmental performance of the three construction methods. The functional unit was defined as the target road condition (2 lanes, 7 m wide and 1 m long) shown in Fig. 2. We hypothesized that the inclined angles of the mountain and road slope would be 35 degrees and 55 degrees respectively. Accordingly, the ratio of cut and fill in the conventional method was set at 3:1, and the ratio of cut and fill for the other two methods was set at 1:3 (Fig. 3).

Fig. 1 Location of case study area.

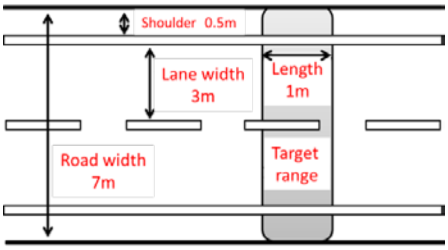

Fig. 2 Functional unit.

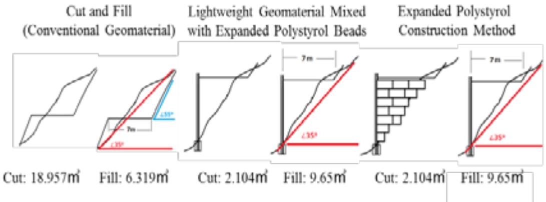

Fig. 3 Set condition of each construction method.

3. SYSTEM BOUNDARY OF EACH CONSTRUCTION METHOD

The system boundary of the cut and fill (conventional method) is shown in Fig. 3. The limestone is transported to the plant for producing stabilizing material, and then the soil, sand, stabilizing material and water are transported to the construction site, where they are mixed and leveled. The cut and fill method is basically maintenance-free. At the waste phase, soil and sand are recycled after the road is demolished.

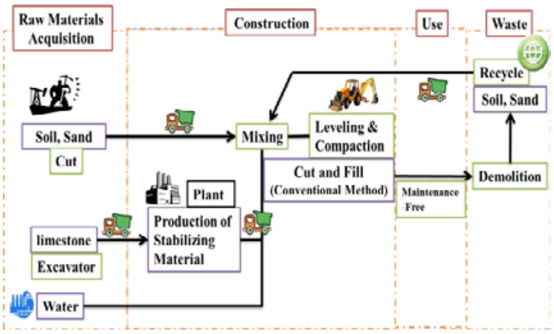

Fig. 3 System boundary of cut and fill method (conventional method).

Fig. 4 shows the system boundary of construction with the lightweight geomaterial mixed with expanded polystyrene beads. Expanded polystyrol beads are produced in the plant during the raw materials acquisition phase. At the construction phase, the limestone is transported to the plant for producing stabilizing material, and then the expanded polystyrol beads, soil, sand, stabilizing material and water are transported to the site, where they are mixed and leveled. This method is also maintenance-free. At present, the recycling method for lightweight geomaterial mixed with expanded polystyrene beads is unknown, but we assumed a blowing separator is used for recycling the soil.

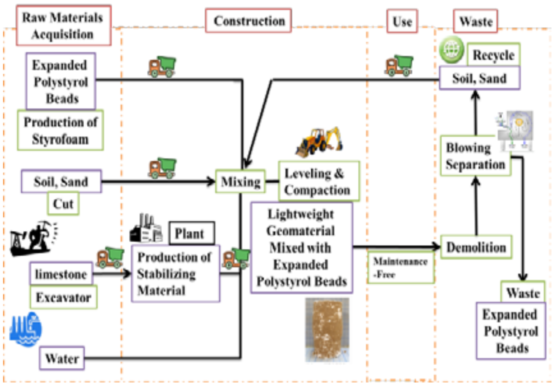

Fig. 4 System boundary of lightweight geomaterial mixed with expanded polystyrene beads.

Fig. 5 shows the system boundary of the expanded polystyrol construction method. Expanded polystyrol beads are produced in the plant during the raw materials acquisition phase, and lightweight geomaterial is mixed with the expanded polystyrol beads at the plant. Also at the plant, the clamping materials that are used for expanded polystyrol construction are manufactured from aluminum produced from imported bauxite and zinc smelt from sphalerites. The soil generated by excavation at the road construction site, styrofoam and clamping materials are all used for expanded polystyrol construction. At the waste phase, all materials are disposed of at the plant after demolition of the road.

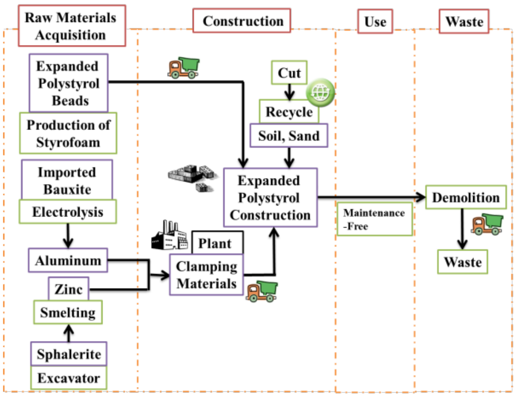

Fig. 5 System boundary of expanded polystyrol construction method.

4. METHOD AND SYSTEM DETAILS

To calculate the total amount of air pollutants and CO_2 emitted by each method, we set the CO_2, SOx and NOx unit (Table 1) and cost unit for each material (Table 2). These units were developed based on data from sources such as the LCA guidelines for building [10], IDEA (Inventory Database for Environmental analysis) [11], the LCA database developed by the Life Cycle Assessment Society of Japan [12], the database of the Express Highway Research Foundation of Japan [13] and the database of JEMAI-LCA PRO [14].”

Table 1 CO_2, SOx and NOx unit.

Life-cycle	Materials	CO_2 (kg-CO2)	SOx (g-SOx)	NOx (g-NOx)
Raw Materials Acquisition	Soil, Sand (kg)	0.001963	0.003407	0.010598
	Limestone (kg)	0.004688	0.000865	0.001547
	EPS (kg)	1.31226	0.255529	1.165096
	Aluminum (kg)	9.218	76.8	30
	Zinc (kg)	1.443	5.92	1.327
Construction	Leveling (㎥)	20.9	28.91883	48.17308
	Compaction (㎥)	12.1	16.74248	27.88968
Transport	20t Truck (Diesel)（km）	1.18	1.45	3.64
	15t Truck (Diesel)（km）	0.962	1.18	2.97
	10t Truck (Diesel)（km）	0.742	0.91	2.229
	4t Truck (Diesel)（km）	0.472	0.56	1.45
	2t Truck (Diesel)（km）	0.323	0.4	1.0
Waste	EPS (kg)	2.64	0.544	1.22
	Metal (kg)	0.366	0.325	0.591
Energy	Electricity (Thermal power plant) (kwh)	0.425	0.17	0.13

The cost unit for each material was estimated using the Input-Output Table of Japan’s Ministry of Internal Affairs and Communications [15]. The power consumption of the blowing separator used for recycling soil and sand for lightweight geomaterial mixed with expanded polystyrene beads was estimated based on an interview with the machinery manufacturer.

The estimated total amounts of air pollutants and CO_2 emissions of each construction method are shown in Tables 3, 4 and 5.

Table 2 Cost unit for each material.

Materials	Unit	JPY
Polystyrene	JPY/kg	209.862
Crushed stone	JPY/kg	2
Limestone	JPY/kg	0.633
Aluminum	JPY/kg	76.539
Zinc	JPY/kg	186.132
Electricity (Thermal power plant)	JPY/kwh	16.19839
Diesel	JPY/L	78.979
Waste (Plastic)	JPY/kg	0.510976
Waste (Metal)	JPY/kg	0.998192
Leveling & Compaction	JPY/m^3	934.2707

Table 3 Air pollutants and CO_2 emissions of cut and fill method.

Materials	Usage	CO_2 (kg-CO2)	SOx (g-SOx)	Nox (g-NOx)	Cost (JPY)
Soil, Sand (kg)	26539.8	52.1	90.4	281.3	53079.6
Limestone (kg)	405.5	1.9	0.4	0.6	256.7
Leveling & Compaction (m^3)	6.3	208.5	288.5	480.6	5903.7
Soil, Sand (kg)	30.0	35.4	43.5	109.2	1077.0
Limestone (kg)	160.0	51.7	64.0	160.0	1579.6

Table 4 Air pollutants and CO_2 emissions of lightweight geomaterial mixed with expanded polystyrene beads.

Life Cycle Stage	Materials	Usage	CO_2 (kg-CO2)	SOx (g-SOx)	Nox (g-NOx)	Cost (JPY)
Raw Materials Acquisition	Soil, Sand (kg)	10615.0	20.8	36.2	112.5	21230.0
	Limestone (kg)	1105.7	5.2	1.0	1.7	699.9
	EPS (kg)	88.9	116.7	22.7	103.6	18656.9
	Soil, Sand (kg)	2944.9	5.8	10.0	31.2	5889.8
Construction	Leveling & Compaction (m^3)	9.7	318.5	440.6	734.0	9015.7
Transport	Soil, Sand (kg)	30.0	28.9	35.4	89.1	877.5
	Limestone (kg)	160.0	51.7	64.0	160.0	1579.6
	EPS (kg)	160.0	51.7	64.0	160.0	1579.6
Waste	Demolition (kwh)	11.9	5.1	2.0	1.5	192.8
	EPS (kg)	88.9	234.7	48.4	108.5	45.4

Table 5 Air pollutants and CO_2 emissions of expanded polystyrol construction method.

Life Cycle Stage	Materials	Usage	CO_2 (kg-CO2)	SOx (g-SOx)	Nox (g-NOx)	Cost (JPY)
Raw Materials Acquisition	EPS (kg)	448.7	588.8	114.6	522.7	94156.5
	Aluminum (kg)	1.2	11.0	91.7	35.8	91.3
	Zinc (kg)	0.9	1.4	5.6	1.2	175.3
Construction	Soil, Sand (kg)	2944.9	5.8	10.0	31.2	5889.8
Transport	EPS (kg)	160.0	75.5	89.6	232.0	1944.1
	Soil, Sand (kg)	30.0	14.2	16.8	43.5	364.5
Waste	EPS (kg)	448.7	1184.5	244.1	547.4	229.3
	Metal (kg)	2.2	0.8	0.7	1.3	2.2

5. RESULT

Fig. 6 shows the estimated air pollutants and CO_2 emissions of each construction method at each life cycle phase. The expanded polystyrol construction method has the largest CO_2 emissions, because a large amount of CO_2 was discharged by production of styrofoam during the raw materials acquisition phase and by disposal of expanded polystyrol beads at the waste phase. The lightweight geomaterial mixed with expanded polystyrene beads had slightly higher SOx emissions than other methods due to higher SOx emissions at the construction phase. The lightweight geomaterial mixed with expanded polystyrene beads had the highest NOx emissions because of high NOx emissions at the construction and transport phases.

Fig. 7 indicates the estimated total life cycle cost of each construction method. The cost of the lightweight geomaterial mixed with expanded polystyrene beads was the cheapest, and the expanded polystyrol construction method was the most expensive. In general, the cost for polystyrol beads at the raw materials acquisition phase was the cause of the cost increase.

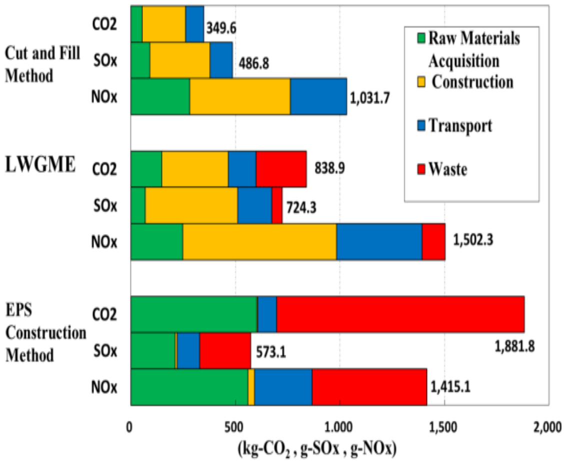

Fig. 6 Estimated amount of air pollutants and CO_2 emissions of each construction method.

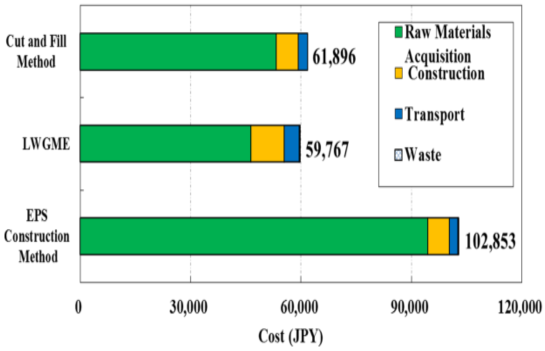

Fig. 7 Estimated total life-cycle cost of each construction method.

6. CONCLUSION

Based on the results of the comparative analysis, we conclude that the cut and fill method (using conventional geomaterials) had fewer environmental impacts than other methods and a relatively low life cycle cost, and also adding the polystyrol materials to the composite geomaterials increases air pollutants and CO_2 emissions at the raw materials acquisition and waste phases. If polystyrol materials are recycled, these emissions might decrease. The lightweight geomaterial mixed with expanded polystyrene beads was the lowest life cycle cost, but it had the highest NOx and SOx emissions than other methods at the construction phase. Thus, it is necessary to improve construction method to decrease environmental load. On the other hand, the expanded polystyrol construction method requires developing the efficient production and recycling method for reducing CO_2 emissions at the waste phase and life cycle cost.

However, further studies need to be conducted, incorporating the viewpoints such as degree of safety, recycle process and external costs into life cycle cost for a fair life cycle impact comparison and assessment.

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