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LIFE CYCLE ASSESSMENT ON RECYCLING OF CONSTRUCTION SLUDGES IN GEOTECHNICAL ENGINEERING FIELDS

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ABSTRACT: Although waste recycling has been promoted in response to increasing environmental awareness in Japan, its marketability is being questioned due to the recycling cost. The ultimate goal of waste recycling is to reduce the environmental load. In this paper, we examined the evaluation method for social environmental efficiency to socially evaluate waste recycling, by incorporating environmental load as an environmental cost in addition to the direct cost. The social environmental efficiency evaluation including consideration of uncertainties is conducted, because waste recycling involves various uncertain elements. As the results, the social environmental significance of construction sludge recycling can be evaluated quantitatively while focusing on the particular construction sludge with a lower recycling rate.

Keywords: Construction sludge; *environmental impact assessment*; *monetary value*; *social and environmental efficiency*; *waste recycling*

1. INTRODUCTION

In Japan, the amount of waste is continuously increasing. Meanwhile, the life-span of the final disposal sites is becoming relatively longer due to promoted reduction and recycling of the waste along with the related technological evolution. However, because it is difficult to build new final disposal sites, further effort is desired for effective handling of waste.

To solve the above problem, it is necessary for us to shift from a mass-consumption society to a recycling-based society. Currently, the "Law for Promotion of Effective Utilization of Resources" enhances the recycle system with, for example, the implementation of collecting and recycling of the products by manufacturers themselves, to build up the recycling-based society, promoting 3R for 69 items in 10 industries. Among them, the construction industry is regarded as a specified recycle-oriented industry and is required to proactively make efforts to utilize recycled resources and parts [1]. In fact, the construction industry accounts for 20% of the total industrial waste emission (2005) and therefore, immediate countermeasures should be implemented. However, even when it is technically possible to recycle construction by-products, they are regarded as waste at the end if there are no end-user demands for such recycled products and facilities for recycling. One of the main factors that inhibit recycling construction by-products is degraded marketability due to the high cost of recycled material compared to virgin material. However, this can be the result of the fact that recycling is considered in terms of only apparent cost (actual cost). The true objective of recycling is environmental conservation to maintain sustainable development. Therefore, in evaluating the business possibilities for recycling waste, not only the actual cost but also the influence on the environment should be considered. In other words, it is important to evaluate various business activities pertaining to recycling waste through their whole life-cycles by socio-environmental efficiency, considering the balance between actual cost and environmental influence, as well as by environmental impact assessment and environmental accounting methods [2] internalizing, assessing and calculating environmental impact. However, the circumstances surrounding recycling waste are complicated by different factors, and it is impossible to reach a simple answer such as recycling material is superior or inferior in terms of socio-environmental efficiency.

This study internalizes not only the direct cost but also the environmental load as environmental cost to review and prototype an evaluation method for socio-environmental efficiency, which evaluates waste recycling socially. Also, the study looks to the recycling of "construction sludge" of which the recycling rate is relatively low among construction-related waste regarded as a recycling resource. For your information, sensitivity analysis and Monte-Carlo simulation are implemented for the reviewed and prototyped evaluation method for socio-environmental efficiency because the construction sludge recycling is prone to various uncertainty factors. Thus, the evaluation method for socio-environmental efficiency is implemented considering the uncertainties associated with construction sludge recycling.

2. CURRENT CIRCUMSTANCES SURROUNDING CONSTRUCTION SLUDGE RECYCLING

2.1 Classification of Construction Sludge

"Construction By-product" refers to all the products gained collaterally via construction work, and categorized into "Surplus Soil" and "Construction Waste".

"Surplus Soil" is earth and sand removed from the construction site and is not classified as the waste prescribed in the "Wastes Disposal and Public Cleansing Act (Waste Disposal Act) (Finally revised in 2008)", and is thus categorized as a recyclable resource. Meanwhile, "Construction Waste" falls into the waste prescribed in the "Waste Disposal Act" and may be referred to as including both general waste and industrial waste.

This study focuses on construction sludge among construction by-products. Construction sludge is defined as "sludge generated in connection with excavating work related to construction and treated as industrial waste prescribed in the "Waste Disposal Act" Also, the "Technical Standard for Recycling Construction Sludge (Draft) (Issues 71 and 71-2, Announcement by engineering Affairs Division of Ministry of Construction)" describes the standard for recycling construction sludge. Under the current legal system, the generators of construction sludge themselves utilize or sell it, or recycle complying with the recycle and utilization system. Also, to support this, the "Recycling Policy for Construction Sludge (Supervised by the Ministry of Construction on November in 1999)" [3] has been issued. However, both standards are too stringent, so that most of the construction sludge is finally disposed as industrial waste.

2.2 Emission and Recycling of Construction Sludge

According to a survey by the Ministry of the Environment, the industrial waste in Japan reached 422 million tons in 2005, increasing by 5 million tons from 2004. Also, as of 2011, the last 20 years saw an overall increase in industrial waste, although the emission amount came in waves [4].

The emission amount of industrial waste by category released by the Ministry of Land, Infrastructure, Transport and Tourism (2005) shows the construction industry accounts for 18.1% with 7.7 million tons, to become in the top 3 [5]. Likewise, construction sludge accounts for 7.5 million tons in emission of industrial waste by item in 2005 (*see* Fig. 1). The emission of construction sludge occupies a relatively small proportion of the total emission of constructual waste. However, as for the final disposal amount of constructual waste by item (2005), construction sludge accounts for 1.9 million tons of a total of 6 million tons. That is, construction sludge accounts for 30% in the final disposal amount (*see* Fig. 2) [6]. Meanwhile, as for the percentage of recycling construction waste in 2005, the total recycling rate of construction waste is 92.2% while the recycling rate of construction sludge is 74.5% (*see* Fig. 3). Therefore, construction sludge recycling may not be enough, compared to other construction waste recycling.

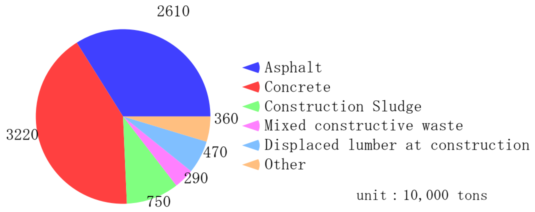

Fig. 1 Emission of construction waste by item (2005)

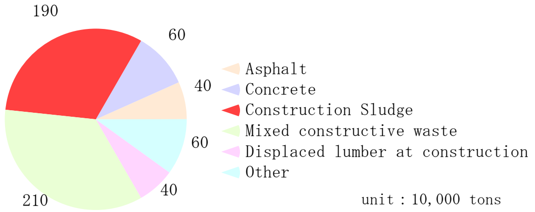

Fig. 2 Final disposal amount of construction waste by item (2005)

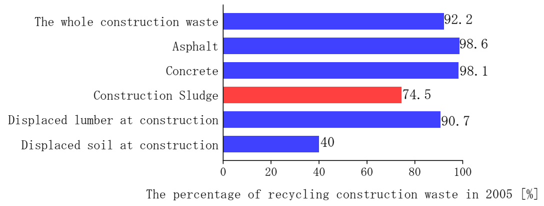

Fig. 3 Construction waste recycling rate (2005)

2.3 Obstacles in Construction Sludge Recycling

There are a variety of recycle processing methods of construction sludge. Generally speaking, because the quality of recycled product from construction sludge depends on the recycle processing method, it is necessary to select a processing method which is the most appropriate for its application. At the same time, selection of the recycling processing method affects the economic efficiency in recycling construction sludge because the recycling cost varies depending on the recycling processing method. One of the largest obstacles in recycling construction sludge is higher cost compared to virgin material such as general commercial earth and newly mined natural soil. Construction sludge is literally muddy, so the processing cost (the direct cost) needs to include the cost of the dewatering process for recycling.

It is desirable that the recycled material from emitted construction sludge is utilized in other construction works. However, according to the actual condition survey of construction byproducts in 2005 [6], only 4% of them were used in other construction works. This is because the number of recycle processing facilities is limited and therefore, long distance transport is often required between the emission site and the recycle processing facility, or between the recycle processing facility and the applicable construction site. That is, the transport cost increases and more air-polluting substances are emitted. Delays in the construction schedule due to unsupplied recycled materials also restrict construction sludge recycling.

The main applications of construction sludge are banking material and backfilling material. Therefore, in recycling construction sludge, not only the processing cost (the direct cost) but also the negative impact of such banking or backfilling material on the environment should be considered and addressed. The factors by which recycling construction sludge causes negative impact on the environment include heavy metals which can be contained in the construction sludge itself and high-alkali due to the solidifying material added in the solidification process [3]. Therefore, when recycled material from construction sludge that can contain environmentally hazardous substances is used, it must be confirmed that such hazardous substances are not eluted from the recycled material, or that the elution level of the hazardous substances are within an environmentally acceptable range [7]. For your information, previous study by Inazumi et al. [8] has showed the usefulness of recycling decreased quantitatively by considering a process delay in processing for recycling owing to unstable supply of construction sludge as well as a variance in the period required for processing for recycling.

3. REVIEW AND PROTOTYPE THE EVALUATION METHOD OF SOCIO-ENVIRONMENTAL EFFICIENCY

3.1 Overview

The emission of waste in human daily life is inevitable. Also, maintaining and developing our current social life level requires a large volume of resource consumption, which results in waste emission. Therefore, to maintain human activities, the important challenge is to form a recycle-oriented society. Taking this into account, a recycle system should be implemented where the costs of the recycling process and of the environmental load are both reducible. However, economic efficiency and reduction in environmental load may conflict with each other. Therefore, to implement the most socially suitable waste recycling, it is important to evaluate the relationship between both. However, simple comparisons are impossible, because the cost and the environmental load have different dimensions. Thus, an effective method to evaluate the relationship between economic efficiency and reduction in environmental load would be to convert the environmental load into a cost-like dimension (cost base). This study utilizes environmental impact evaluation and environmental accounting methods [2] to assess quantitatively the cost and environmental load associated with the recycling of general construction waste, and to review and prototype the evaluation method of socio-environmental efficiency.

3.2 Life Cycle Assessment

When comparing virgin material and recycled material from construction waste with the evaluation of socio-environmental efficiency, the evaluation should not be implemented simply regarding production of the materials. Virgin material must be produced from new material or mining a new natural resource, and so on. Particularly, it is presumed that mining causes a major impact on the environment. It is presumed that producing recycled material also has a major impact on the environment because it often requires long distance transport between the emission point of construction waste and the facility for recycle processing, and between the facility and the applicable construction site. Therefore, to implement the evaluation of the socio-environmental efficiency, various environmental loads such as resource consumption and emission amount need to be considered for whole life cycles of virgin material and recycled material, from mining resources and production to utilization and disposal.

Life cycle assessment (LCA) [9] is a method to evaluate the whole life-cycle scientifically, quantitatively and objectively. The procedures of LCA are shown below.

(i) Define the objective and analysis scope: Set the objective and analysis scope of LCA evaluation.
(ii) Inventory Analysis: Calculate the environmental load amount emitted into the environment from the analysis subject, and the input from the environment.
(iii) Environmental Assessment: Classify the results gained from Inventory Analysis into environmental impact items such as climate change and air pollution, and implement grouping and integrating, between evaluation of the impact on such items (characterization) and the environmental impact items, to create a single index.
(iv) Interpretation: Review the findings based on the results obtained.

In the above LCA method, step (iii) is called life cycle impact assessment (LCIA). Among many LCIAs, the life cycle impact assessment method based on endpoint modeling (LIME) [9] enables calculation of the environmental load amount using the cost base because it utilizes monetary value (yen) as an integrated index for conjoint analysis.

Based on the current situation of recycling construction sludge in Japan, this study analyzes the direct cost and environmental cost considering the life cycles of virgin material and recycled construction sludge. The evaluation of socio-environmental efficiency covers the steps of material production, transport by vehicle, and construction of soil structure, but the manufacture of heavy equipment and transport vehicles, and the material required for construction of each facility are not considered. More specifically, the direct cost and environmental cost associated with construction of recycle processing facilities, and so on, are not considered. Figures 4 and 5 show the direct cost and environmental cost that can be assumed in each process.

3.3 Quantify the Direct Cost

To implement construction waste recycling, the actual cost such as transport cost and recycle processing cost is required. In this study, such costs are referred to as "direct cost". The direct cost has been regarded as the standard for decision making in a mass-consumption society. Further, the direct cost roughly falls into initial cost and running cost (processing cost, transport cost and storing cost) [10].

The direct cost is calculated by Eq. (1). That is, Eq. (1) is applied to the production of virgin and recycled materials and the waste disposal process. The factor shown in Eq. (1) is the unit cost per construction work unit.

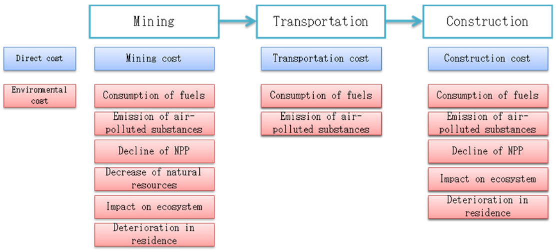

Fig. 4 Direct and environmental cost factors in the assumed LCA and each process (Virgin material)

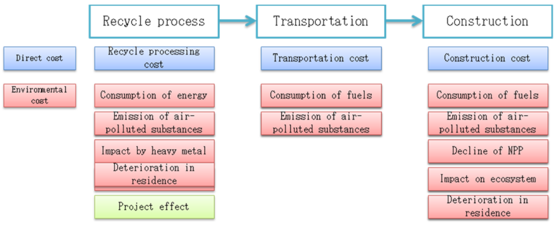

Fig. 5 Direct and environmental cost factors in the assumed LCA and each process (Recycled material)

$$C = C_I + C_S + C_T + C_K \qquad C_S = WS \quad C_T = WLT \quad C_K = WDK \tag{1}$$

Where, C: direct cost (yen), C_I: initial cost (yen), C_S: processing cost (yen), C_T: transport cost (yen), C_K: storage cost (yen) W: material mass (m^3), S: cost required for processing each material (yen/m^3), L: transport distance (km), T: cost required for transport (yen/t·km), D: storage time (day), and K: cost required for storing each material (yen/t·day)

3.4 Quantify the Environmental Cost

The environment is an asset which provides human beings with a wide variety of valuable functions and services for free. However, in economy-oriented societies, such environmental value is not always evaluated properly. One of the reasons is that the environment is regarded as an unlimitedly available property and its value has not been quantified. Therefore, environment conservation has not been directly linked to economical benefit and environmental destruction has not stopped. The objective of recycling is breaking the above social structure, and in that sense, it is necessary to help people understand environmental value by converting it into monetary value. In this study, occurring environmental load, converted into a cost base similar to direct cost, is referred to as "environmental cost".

To quantify the environmental cost, there is the Original Unit Method where the emission amount of substances that cause environmental load is evaluated using original units of monetary value defined in various manuals, and so on [11]. Also, the evaluation methods for environmental cost, subject to the impact on ecosystem and environmental values gained from nature and therefore difficult to quantify, are roughly classified into Direct Method, based on stated preferences obtained mainly by direct interviews with people, and Indirect Method based on revealed preferences obtained indirectly from economic activities [11]. The important point when calculating the environmental cost is to properly extract the factors that can impact on the environment, and then, to calculate the environmental cost with the extracted factors using appropriate evaluation methods. As stated above, there are many evaluation methods for environmental cost and the coverage and calculation methods depend on those methods. Therefore, the most appropriate evaluation method should be selected according to the element characteristics and the evaluation objective.

In the evaluation of socio-environmental efficiency for construction waste recycling implemented in this study, the environmental cost factor especially focused on is as Eq. (2). Equation (2) is applied to the production of virgin and recycled materials, and waste disposal processing. Each factor shown in Eq. (2) is value per construction work unit. Here, in extraction of such environmental cost factors, we refer to the outcome by [12] and [13].

$$E = E_O + E_T + E_{C1} + E_{C2} + E_{C3} + E_{C4} \tag{2}$$

Where, E: environmental cost (yen), E_O: environmental cost associated with facility operation (yen), E_T: environmental cost associated with transport (yen), E_{C1}: environmental cost associated with common good function such as forest (yen), E_{C2}: environmental cost associated with impact on ecosystem (yen), E_{C3}: environmental cost associated with picking natural resources (yen), and E_{C4}: environmental cost associated with deteriorated residential environment (yen)

3.4.1 Environmental cost associated with facility operation

Environmental load occurs due to activities such as mining, recycle processing and final disposal. This study considers the environmental load incurred by such activities, as emitted carbon dioxide (CO_2) volume. To quantify CO_2, the resource and energy volume used in each activity is multiplied by the CO_2 emission coefficient (*see* Table 1) [14] released by the Ministry of Land, Infrastructure, Transport and Tourism, and so on. Further, to define Eq. (3) as environmental cost associated with CO_2 emission, the CO_2 emission amount is multiplied by the original unit of CO_2 monetary value.

Table 1 CO_2 emission coefficient derived from energy

Energy	The CO_2 emission coefficient
Electric power	0.555t-CO_2/kWh
Gasoline	2.322kg-CO_2/L
Light oil	2.619kg-CO_2/L
Paraffin oil	2.489kg-CO_2/L
A heavy oil	2.710kg-CO_2/L
B·C heavy oil	2.982kg-CO_2/L
LPG	3.000kg-CO_2/L
LNG	2.698kg-CO_2/L
Town gas	2.080kg-CO_2/L

Table 2 CO_2 emission coefficient derived from transport

Means of transportation	The CO_2 emission coefficient
By medium-duty truck	178g-CO_2/t·km
By pickup truck	819g-CO_2/t·km
By lightweight truck	1,933g-CO_2/t·km
By railroad traffic	21g-CO_2/t·km

$$\begin{aligned} &E_O = \textit{original unit of } CO_2 \textit{ monetary value} \times CO_2 \textit{ emission volume} \\ &CO_2 \textit{ emission volume} = CO_2 \textit{ emission coefficient} \times \textit{resource and energy volume used} \end{aligned} \tag{3}$$

There are different evaluation methods regarding *the original unit of CO_2 monetary value*, and the government and corporations set various values based on previous studies [5]. This study adopts 2,890 yen/t-CO_2, which is specified as the *original unit of CO_2 monetary value* in Japan by the Ministry of Land, Infrastructure, Transport and Tourism [14].

3.4.2 Environmental cost associated with transport

In the construction of earth structures, transport vehicles are used when earth materials are transported from the recycle facility to the construction site and when construction waste is transported from the source construction site to the final disposal site. Here, the air-polluting substances, mainly consisting of CO_2 and emitted when transport vehicles are used, is regarded as environmental load. It is calculated as Environmental cost associated with transport shown as Eq. (4), using the original unit of transport-related emission (CO_2 emission volume emitted in transporting a 1 ton load for 1 km) (*see* Table 2) [14].

$$E_T = \text{original unit of } CO_2 \text{ monetary value} \times \text{original unit of transport emission} \times W \times L \qquad (4)$$

Where, *W*: transported earth volume (t) and *L*: transported distance (km)

3.4.3 Environmental cost associated with common good function such as forest

Let us consider mining, construction of facilities and damage to net primary productivity (*NPP*) of plants cut down when the final disposal is implemented. *NPP* is the volume of produced organic substance via photosynthesis fixing CO_2 in the air. That is, in other words, it is the reduction volume of CO_2 by plants in one unit area [5]. Mining, construction of facilities and final disposal cause land occupancy and changed NPP_a. ΔNPP is *NPP* loss between changed vegetation of NPP_a and original vegetation of NPP_p and calculated as Eq. (5) (*see* Fig. 6). Here, it is assumed that vegetation recovers linearly and the recovery duration is 30 years.

$$\Delta NPP = (NPP_p - NPP_a) \times T_a + \frac{1}{2} \times (NPP_p - NPP_a) \times T_{a \to p} \qquad (5)$$

Where, ΔNPP: primary production *NPP* loss, NPP_p: primary production (t-CO_2/year·ha) in original vegetation, NPP_a: primary production (t-CO_2/year·ha) after the land is changed, Ta: duration (years) of land occupancy, and Ta->p: duration (years) required for recovering the land

Environmental cost associated with common good function such as forest is defined as Eq. (6) and is multiplied by land area (*S*) and the original unit of CO_2 monetary value.

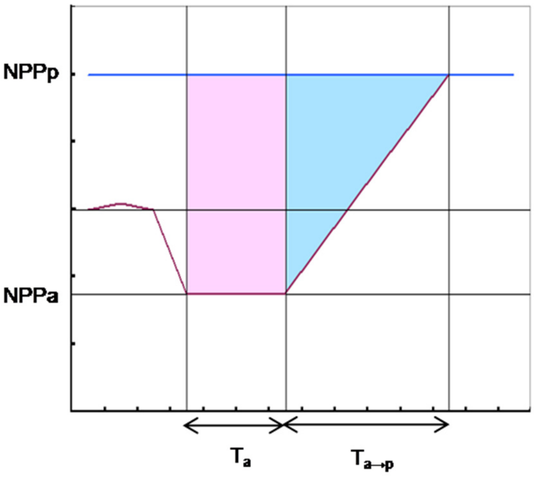

Fig. 6 Image of loss of net primary productivity (NPP)

Table 3 Monetary conversion coefficient regarding ecological damage due to heavy metals

Heavy metal	Water discharge	Soil discharge
Cadmium	8.53E+05	6.45E+05
Lead	6.55E+05	4.95E+04
Hexavalent chromium	6.72E+04	5.08E+04
Arsenic	1.47E+05	1.11E+05
Total mercury	4.06E+06	3.07E+06
Selenium	1.03E+05	7.76E+04

$$E_{CI} = \text{original unit of } CO_2 \text{ monetary value} \times \Delta NPP \times S \qquad (6)$$

3.4.4 Environmental cost associated with impact on ecosystem

When land is used for mining, construction of recycle processing facilities and final disposal sites, the surrounding ecosystem is affected. Here, the impact on the ecosystem represents the increase in the level of risk for extinction of certain species [9]. However, the impact on the ecosystem due to land usage is mainly limited to the plant species targeted by the red list, so it’s not practical to evaluate it. Therefore, the impact on the ecosystem due to land usage is not considered in this study.

The impact on the ecosystem due to heavy metals contained in recycled materials should be evaluated not only for endangered species but also other species. Therefore, environmental cost associated with impact on the ecosystem due to heavy metals that can be contained in recycled material is shown as Eq. (7), and the contained amount of heavy metals is multiplied by the *monetary conversion coefficient* shown in Table 3 [8].

$$E_{C2} = \text{monetary conversion coefficient} \times \text{contained amount of heavy metals} \tag{7}$$

3.4.5 Environmental cost associated with mining natural resources

The natural resource in this study refers to the mineral resource and soil and stone resource. Environmental loads that can occur by mining natural resources include damage to human health, impact on the ecosystem and impact on land usage. This study focuses on the reduction of resource stock. End points of reduction of resource stock can be regarded as depletion of resources and economic damage for future generations associated with increased mining costs and refining costs. Specifically, as the mining of mineral resources proceeds and the metal proportion of ore decreases, the energy required for refining and the related waste volume becomes enormous. There is a methodology to calculate such increased volume as future economic damage [7]. Therefore, for mining mineral resources, environmental cost is defined as shown in Eq. (8).

$$E_{C3} = \text{monetary conversion coefficient} \times \text{mining amount of mineral resources} \tag{8}$$

Meanwhile, as for mining soil and stone resources, although they cannot be regarded as unlimited, because various legal regulations related to natural conservation restrict the available amount, it is difficult to consider in terms of stock reduction of resources, because these resources are usually used for additional soil, backfilling and land formation. Therefore, soil and stone resources mining is not considered for construction sludge recycling.

3.4.6 Environmental cost associated with deteriorated residential environment

The decline in range in land price, when mining or construction of a recycle processing facility is implemented, is defined as environmental cost regarding deteriorated residential environment. Here, the environmental cost regarding deteriorated residential environment adopts the value calculated with the Hedonic Price Method [15] and is shown as Eq. (9).

$$E_{C4} = \text{original unit of deteriorated residential environment} \times \text{soil and stone resource amount} \tag{9}$$

Where, *original unit of deteriorated residential environment*: (yen/m^3) and *soil and stone resource amount*: mined amount of virgin material and the recycled material volume (m^3).

3.5 Project Effect in Construction Waste Recycling

Recycling construction waste enables reduction of the cost required for disposal of it [16]. Therefore, the cost reduction amount required for the waste disposal should be recorded as the project effect for the recycling. The appraisal value is calculated with construction waste volume multiplied by the final disposal processing unit price, which is shown as Eq. (10).

$$B = W \times S \tag{10}$$

Where, B: project effect in construction waste recycling (yen), W: construction waste volume (m^3), and S: final disposal processing unit price (yen/m^3)

3.6 Total Cost

In the evaluation of socio-ecological efficiency, the total cost shown as Eq. (11) is defined as one of the indexes for socio-environmental efficiency. The total cost can be regarded as social cost considering environmental impact.

$$T = C + E + B \tag{11}$$

Where, T: total cost (yen), C: direct cost (yen), E: environmental cost (yen), and B: project effect in recycling (yen)

3.7 Consideration of Uncertainty

As stated above, a variety of data is required to evaluate the socio-environmental efficiency for construction waste recycling. Moreover, the data changes according to each situation. For example, depending on where a certain recycle processing facility is based, the recycled material needs to be transported to construction sites in different areas. That is, the transport distance depends on the location. Also, even with the same construction waste, the recycle processing costs may be different if their forms are different. These are collectively called “data fluctuation”. Further, as for calculation of the processing cost (direct cost) and environmental cost, each data is not linked linearly. Also, because evaluation for environmental impact and environmental accounting are relatively new fields, they include uncertainty that quantitative environmental value might not be evaluated accurately. The data fluctuation and uncertainty may cause large divergence between the evaluation calculated as the base case and actual evaluation [17]. As a result, actions that are not in line with socio-environmental efficiency may be taken to give further environmental load. To prevent such situations, it is necessary to consider data fluctuation and uncertainty.

3.7.1 Sensitivity analysis

One of the methods to consider data fluctuation and uncertainty is sensitivity analysis [18]. Sensitivity Analysis is the method where output shift is detected by changing only one uncertainty factor among multiple uncertainty factors as input, and fixing other factors to the base case. Sensitivity Analysis divides are categorized into two methods; one is an uncertainty factor changes its value at a consistent rate, and the second one is the value changes from the maximum value to the minimum value. In this study, the latter is adopted to enhance integrity with the actual situation. Here, implementation of sensitivity analysis on all uncertainty factors allows us to know the variance ranges of all outputs. That means it is possible to know the impact variance per each uncertainty factor as input. Utilizing the obtained result enables us to implement countermeasures against impeditive uncertainty factors.

3.7.2 Monte-Carlo simulation

While sensitivity analysis is the method to evaluate only one uncertainty factor, Monte-Carlo simulation changes all uncertainty factors at the same time to know all the combinations that can occur. Implementation of Monte-Carlo simulation allows us to obtain the frequency distribution of output and it's often used to calculate risks in projects. A similar method is Best Case / Worst Case Analysis [19]. In this method, the risk analysis is implemented only by the maximum and minimum values of output. However, the obtained result may be divergent from the actual result and it would not be practical. Therefore, this study adopts Monte-Carlo simulation.

4. SOCIO-ENVIRONMENTAL EFFICIENCY IN CONSTRUCTION SLUDGE RECYCLING

4.1 Overview

In the **3.**, the evaluation of socio-environmental efficiency method in recycling construction waste was reviewed and prototyped. In this chapter, for recycling construction sludge, which is one of the construction wastes, evaluation of socio-environmental efficiency of virgin material (which is not recycled earth material) and recycled material (recycled material from construction sludge) are implemented. Figure 7 shows a simple

Fig. 7 Overview of recycling construction sludge as ground material

Table 4 Minimum, median and maximum values of the uncertainty factors

	The minimum value	The median value	The maximum value
The volume of compacted soils (m^3)	-	300	-
Transported distance in virgin materials (km)	0	2.5	5
Transported distance in recycling materials (km)	10	20	25
Mining cost (Yen/m^3)	1,000	3,000	5,000
Recycling processing cost (Yen/m^3)	2,000	5,000	8,000
Unit cost of transportation (Yen/km·t)	58	69	83
The rate of change of soils	1.26	1.47	1.70
Δ NPP (t-C/year·ha)	0	2	9
Heavy metal contents (lead) (mg/kg)	0	23.1	150
Area (ha)	-	0.1	-
Original unit of CO_2 monetary value (Yen/t-CO_2)	700	2,890	9,425

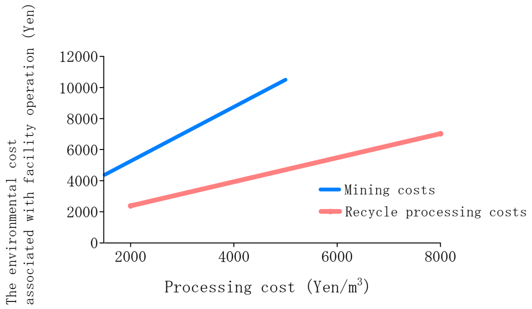

Fig. 8 Relationships between processing cost and environmental cost associated with facility operation

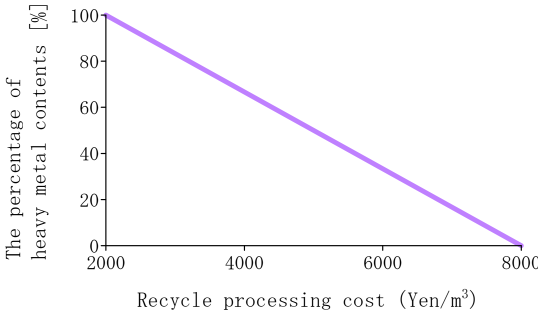

Fig. 9 Relationship between the recycle processing cost and content rate of heavy metals

image of construction sludge recycling as ground material.

4.2 Prerequisite

The prerequisites when implementing evaluation of socio-environmental efficiency regarding the recycling of construction sludge as ground material are as follows:

(1) The set soil volume of earth structure to construct is 300m^3.

(2) For each uncertainty factor, the minimum value, median (base case) and the maximum value shown as Table 4 are set. As the median, the average value obtained via literature research [3], [10], [12] or the value obtained by hearing is used.

(3) Recycle processing of construction sludge is stabilization.

(4) The unit price of mining cost and recycle processing cost is assumed to depend on consumed material and energy, and as the processing cost increases as shown in Fig. 8, the environmental cost associated with facility operation also increases.

(5) The soil conversion factor is considered in mining. Soil volume after mining becomes larger than that after compaction due to added gaps and air spaces during mining. This change rate of soil volume is called “soil conversion factor”

(6) The qualities of virgin material and recycled material are assumed to be the same and the construction methods have no differences.

(7) There is no delay in the construction schedule when recycled material is used. In other words, the storage cost is not considered.

(8) Construction material for earth structures (virgin material and recycled material) is not wasted and is fully used.

(9) The heavy metal that can be contained in construction sludge is lead (Pb).

(10)It is assumed that the heavy metal that can be contained in recycled material decreases as shown in Fig. 9 when the recycle processing cost increases.

The heavy metal that can be contained in construction sludge may be an obstacle for recycling, although there have been few cases in which heavy metals are contained in recycled material [1]. Also, no countermeasures against contained heavy metals are mentioned in the “policy for recycling construction sludge” [3] edited by the Construction Ministry. Therefore, the environmental cost is calculated in two ways; one in which the contained heavy metal is considered, and the other one in which it is not. In the case of no heavy metals contained, the environmental cost associated with the ecosystem is not considered.

4.3 Evaluation Based on Sensitivity Analysis

Figure 10 is the result of sensitivity analysis of each uncertainty factor against the total cost in construction sludge recycling. According to this result, the total cost becomes smaller in descending order of “recycled material when contained heavy metals are not considered”, “virgin material” and “recycled material when contained heavy metals are considered”. However, the total cost in recycled material is likely to fluctuate.

As for “virgin material”, the mining cost accounts for a relatively large proportion of the total cost. Meanwhile, for “recycled material when contained heavy metals are not considered”, the recycle processing cost accounts for a relatively large proportion of the total cost (*see* Fig. 10). This is because the environmental cost is small compared to the direct cost and so the direct cost has a dominant influence on the total cost. Therefore, reducing the direct cost is considered to be essential to promote construction sludge recycling. Meanwhile, as for “recycled material when contained heavy metals are considered”, due to the heavy metals contained in the recycled material, the environmental cost associated with the ecosystem has more influence on the total cost, compared to the recycle processing cost (the direct cost) (*see* Fig. 10). That is, for "recycled material when contained heavy metals are considered", the environmental cost should be more focused than the direct cost, and the amount of heavy metals that can be contained in construction sludge is important.

In sensitivity analysis, quantification of the impact by output from one uncertainty factor is implemented. However, all uncertainty factors may have an influence on actual recycling. Therefore, it is necessary to implement Monte-Carlo simulation and the related risk evaluation of recycling projects considering all uncertainty factors.

4.4 Evaluation Based on Monte-Carlo Simulation

In evaluation using Monte-Carlo simulation, probability distribution is given to each uncertainty factor, and determines the value of the uncertainty factor by extracting values randomly from the cumulative probability distribution. Further, this is implemented on all the uncertainty factors to calculate the total costs of virgin material and recycled material. Also, appraisal value is calculated by subtracting the total cost of recycled material from the total cost of virgin material. If the appraisal value is 0 or more, the recycled material is superior to the virgin material in terms of total cost. If the appraisal value is less than 0, it means the virgin material is superior to the recycled material in terms of total cost. For your information, the obtained result can be understood as a probability distribution and it enables you to clarify advantages of virgin and recycled materials respectively from each result according to the target situation.

As prerequisites to implement Monte-Carlo simulation, the minimum value, median (base case), the maximum value and triangular distribution are set to the probability distribution of each uncertainty factor as shown in Fig. 11 to test 1,000 times with uniform random numbers. The earth volume after compaction is 300m^3 and the original unit of CO_2 monetary value is fixed to 2, 890 yen/t-CO_2.

Figure 12 shows the result of Monte-Carlo simulation focusing only on the direct cost as a histogram representing frequency distribution. This allows us to infer that in the evaluation focusing on the direct cost, there are few cases in which recycled material becomes more advantageous and it is difficult to promote the construction sludge recycling with the conventional idea in which the direct cost is prioritized.

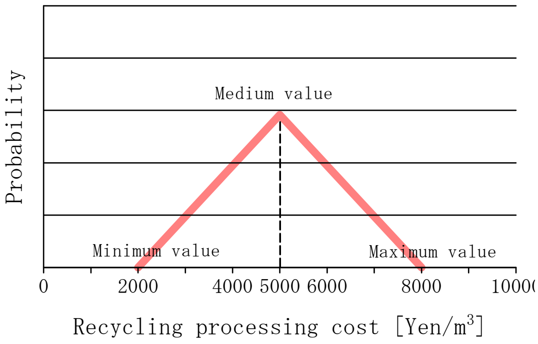

Fig. 11 An example of probability distribution for a uncertainty factor

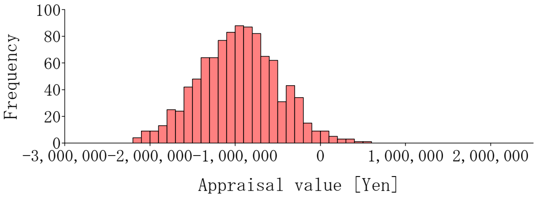

Fig. 12 Result of Monte-Carlo simulation for appraisal value focusing on direct cost

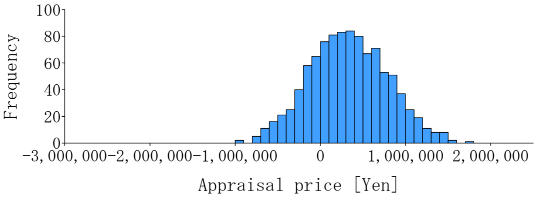

Fig. 13 Result of Monte-Carlo simulation for appraisal value focusing on total cost (Recycled material when contained heavy metals are not considered)

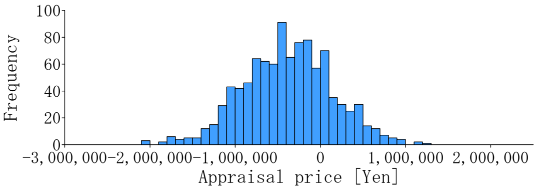

Fig. 14 Result of Monte-Carlo simulation for the appraisal value focusing on total cost (Recycled material when contained heavy metals are considered)

Figures 13 and 14 are the results of Monte-Carlo simulations focusing on the total costs using the evaluation method for socio-environmental efficiency and show two patterns of "recycled material when contained heavy metals are not considered" and "recycled material when

Table 5 Correlation coefficient of the uncertainty factors and appraisal values

Uncertainty factors	Heavy metals are not considered	Heavy metals are considered
The volume of natural soils	-0.0005	0.0433
Mining cost	0.5026	0.4465
The volume of excavated soils	0.0527	0.0084
Transported distance in virgin materials	0.1496	0.1528
Transported distance in recycling materials	-0.2781	0.2285
Unit cost of transportation	-0.1134	-0.0674
ΔNPP	0.0317	-0.0109
Recycling processing cost	-0.7805	-0.1433
Heavy metal contents	-	-0.7633

contained heavy metals are considered". As for "recycled material when contained heavy metals are not considered", cases in which the appraisal value is 0 or more, in other words, "recycled material when contained heavy materials are not considered" is superior to "virgin material" in terms of total cost makes up 75% of total trials. And so, it can be evaluated that the socio-environmental efficiency of "recycled material when contained heavy metals are not considered" is generally good compared to that of "virgin material". Meanwhile, as for "recycled material when contained heavy metals are considered", cases in which the appraisal value is 0 or more makes up 23%. And so, it can be evaluated that the socio-environmental efficiency of "recycled material when contained heavy metals are considered" is inferior to that of "virgin material". However, compared with Fig. 12, it is found that the evaluation with the total cost considering environmental load as well as the direct cost enhances the significance of construction sludge recycling.

However, there are many cases in which recycling is not required if the total cost is considered. Therefore, analysis to determine whether recycling is required or not should be implemented. Nevertheless, analysis of many uncertainty factors is tedious, and the analysis cost and the delay in the construction schedule may be obstacles to recycling. Thus, we should focus on only influential uncertainty factors to implement the analysis. Then, correlation between uncertainty factors and appraisal values was calculated. Tables 5 and 6 show the obtained correlation and correlation strength. Here, positive correlation means that as an uncertainty factor increases, the appraisal value also increases, and negative correlation means that as an uncertainty factor increases, the appraisal value decreases. In Table 5, the mining cost shows moderate positive correlation while the recycle processing cost shows strong negative correlation for "recycled material when contained heavy metals are not considered". Meanwhile, the mining cost shows moderate positive correlation while the contained amount of heavy metal shows strong negative correlation for "recycled material when contained heavy metals are considered" Also, the transport distance involved in producing recycled material shows weak negative correlation. Judging from such results, mining costs, recycle processing costs and the contained amount of heavy metals are especially critical in analyzing the socio-environmental efficiency of recycled material. These are similar to the results obtained in the sensitivity analysis. Also, it is shown that transport distance can be one of the obstacles to construction sludge recycling.

Table 6 Strength of correlation coefficient

±0.7 - ±1	High correlation
±0.4 - ±0.7	Medium correlation
±02 - ±0.4	Low correlation
±0 - ±0.2	Little correlation

4.5 Evaluation Based on Social Cost-Benefit Analysis

Japan has promoted efforts to reduce environmental load and therefore the investment (cost) on the environment increases every year. According to the Actual Condition Survey on Investment on Environment in 2009 implemented by the Ministry of the Environment [20], the total investment amount on environmental conservation is 5, 522.3 billion yen and the capital investment accounts for 1, 523.2 billion yen. However, it is a concern that such significant investment on efforts for environment conservation might largely impact on the domestic economy.

Although direct cost including recycle processing cost and transport cost increases, implementing the construction sludge recycling allows us to obtain returns (benefits) such as reduction of environmental load and project effect pertaining to the recycling. However, if the recycling generates little return although enormous cost is invested, it is difficult to implement such recycling in reality. To handle the above situation, it is necessary to analyze the relationship between increasing direct cost and return (social cost-benefit analysis) [21]. Therefore, the social cost-benefit rate is used for the evaluation. The *social cost-benefit rate* is shown as Eq. (12).

$$\text{Social cost-benefit rate} = \frac{\text{Environmental load reduction} + \text{Project effect}}{\text{Investment amount}} \qquad (12)$$

The investment amount means the difference between the direct cost associated with using "virgin material" and the direct cost associated with using "recycled material". The environmental load reduction means the amount of reduction of the environmental load because of using "recycled material" instead of "virgin material". The project effect of the recycling is as described in **3.5**. The social cost-benefit rate consists of the denominator of the investment amount and the numerator of the project effect brought by the recycling, and the environmental load reduction which is a return of the implemented recycling. In this study, the environmental load is treated as environmental cost.

In the base case, the social cost-benefit rate can be calculated as 1.21 for "recycled material when contained heavy metals are not considered" and 0.94 for "recycled material when contained heavy metals are considered". The social cost-benefit rate is, in other words, the indicator of return (benefit) to investment amount per unit (cost). In conclusion, it is considered that construction sludge recycling can provide a relatively reasonable return to the invested amount.

Figures 15 and 16 show the result of Monte-Carlo simulation using the social cost-benefit rate. If the social cost-benefit rate is negative, it means the environmental load increased although recycling was implemented. As for "recycled material when contained heavy metals are considered", the social cost-benefit rate is high while the investment amount is small. That means the reduced investment amount can help to increase the social cost-benefit rate. However, please note that in such case the project effect as a result of recycling is assumed consistent. The social cost-benefit rate converges to around 0.7 as the investment amount increases. Meanwhile, for "recycled material when contained heavy metals are considered", although high variability of the social cost-benefit rate is seen when the investment amount is relatively small, the social cost-benefit rate converges to around 0.6 as the investment amount increases. That is, for "recycled material when contained heavy metals are considered", the social cost-benefit rate converges to a certain value as the costs such as recycle processing cost increase. The high variability of the social cost-benefit rate when the investment amount is relatively small seems to depend on the contained amount of heavy metal. Therefore, before construction sludge recycling is implemented, scrutiny regarding the contained amount of heavy metal is required. In addition, to set the standard of social cost-benefit rate, further discussion considering the social economic situation will be required.

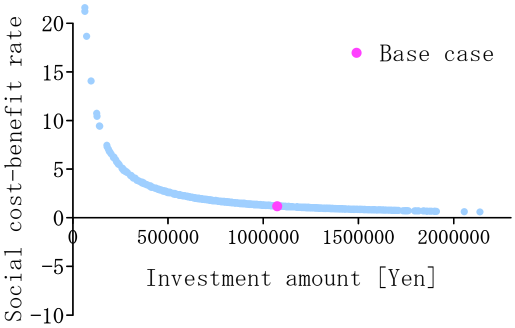

Fig. 15 Result of Monte-Carlo simulation for the appraisal value focusing on social cost-benefit rate (Recycled material when contained heavy metals are not considered)

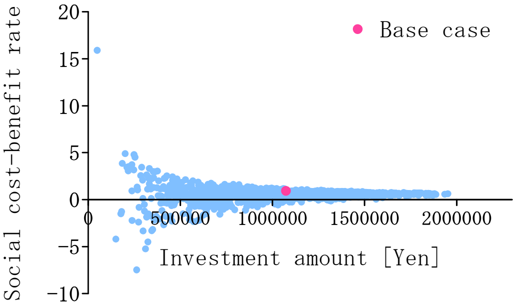

Fig. 16 Result of Monte-Carlo simulation for the appraisal value focusing on social cost-benefit rate (Recycled material when contained heavy metals are considered)

5. CONCLUSIONS

In this study, the evaluation method of socio-environmental efficiency to socially evaluate waste recycling was reviewed and prototyped by internalizing not only direct cost but also environmental load as environmental cost. Specifically, because waste recycling involves different complicated factors, Sensitivity Analysis and Monte-Carlo simulation considering the uncertainties were utilized to implement the evaluation of socio-environmental efficiency.

The obtained results are as follows:

(1) In the evaluation method of socio-environmental efficiency associated with construction waste recycling, from the environmental cost depending on only CO_2 emission, to the environmental load that could not be converted to CO_2 emission could be calculated as a cost base. This enabled the factors in different dimensions, i.e., environmental load and direct cost, to be integrated into the new index - total cost.

(2) By implementing the evaluation of socio-environmental efficiency with Sensitivity Analysis, it was revealed that the major influential factors for construction sludge recycling are mining cost, recycle processing cost and contained amount of heavy metals.

(3) By implementing the evaluation of socio-environmental efficiency with Monte-Carlo simulation, the uncertainties of the assumed factors were considered and it was revealed that the relative significance of construction sludge recycling compared to using virgin material is enhanced with the evaluation using the total cost.

(4) The social cost-benefit rate was used for the evaluation of socio-environmental efficiency in construction sludge recycling. It was revealed that for “recycled material when contained heavy metals are not considered”, the social cost-benefit rate increases as the processing cost (the direct cost) is reduced, while for “recycled material when contained heavy metals are considered”, the social cost-benefit rate converges into a certain value as the processing cost (the direct cost) increases.

In the future, the time factor should be integrated into this evaluation method. Also, the calculation method of the environmental cost should be reviewed more precisely, because any future change in the environmental value may also lead to changes in original units and monetary conversion coefficients related to the environmental influence.

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