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Evaluation Methods for Environmental Impact ~A Case Study of Ecocement Production~

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Life Cycle Assessment (LCA) is the most popular methods to evaluate environmental impact. However, it has many problems, such as the treatment of disposal and method of impact analysis. In this study, we applied three methods: conventional LCA, exergy analysis ($E^{x}A$), and Total Materials Requirement (TMR) to evaluate the environmental impact of the ecocement production process. The "Zero emission" type system boundary is used in our paper, in which disposal of materials is assumed to be as completely harmless substances. In the $E^{x}A$, the amount of the exergy of wasted materials is calculated as the potential impact. In the TMR, amounts of direct and indirect materials engaged by mining and discarding of the products are estimated. The effect of waste recycling for cement production is evaluated by various viewpoints and the results are compared and discussed.

Key Words: Life Cycle Assessment, Exergy Analysis, Total Materials Requirement, Ecocement

1. INTRODUCTION

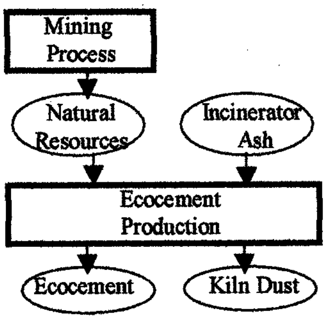
The purpose of this study is to examine the various evaluation methods for environmental impact. LCA is the most popular and fundamental method. However, it has problems, for example, how to decide the system boundary of inventories, how to integrate the environmental impact, how to calculate the effect of recycling, and so on. To solve these problems and to improve evaluation methods for environmental impacts, we examined the problems from various viewpoints. Because environmental problems have a lot of aspects and only one viewpoint is not enough to analyze the impacts. To evaluate the environmental impacts from various viewpoints, we used two other methods, $E^{x}A$ (Exergy Analysis) and TMR (Total Materials Requirement), in addition to LCA.

In this study, the ecocement production process is evaluated by the three ways: LCA, $E^{x}A$ and TMR. Cement is used extensively in building the infrastructure of a society. Besides, it is possible to use many kinds of waste as feedstock or fuel in the production process of cement. Ecocement is the name of a kind of cement that uses more than 500kg of incinerator ash per 1000kg product, so it is expected to decrease the environmental impact by means of cascade use of waste.

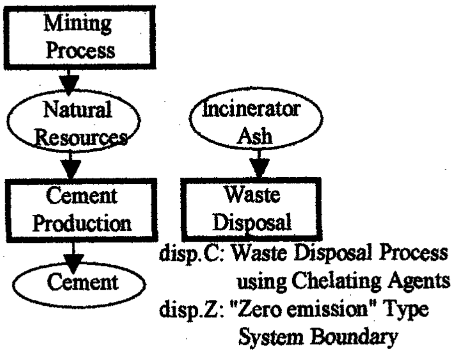
2. EVALUATION

2.1 LCA (Life Cycle Assessment)

Energy consumption and amounts of CO_2 per 1000 kg cement production are evaluated in our LCA. The evaluation processes are shown in Figure 1. We compared two different processes: the first is an ecocement production process and the second is a process that makes portland cement with only natural



Ecocement Production Process (Process-EC)



disp.C: Waste Disposal Process using Chelating Agents
disp.Z: "Zero emission" Type System Boundary

Portland Cement Production Process (Process-PC)
+
Waste Disposal (disp.C or disp.Z)

Figure 1 System Boundary

resources. We call them process-EC and process-PC, respectively. In the process-PC, to compare the loads of two processes, we added the loads of waste disposal that deal with incinerator ash used in process-EC. Furthermore, two types of system are assumed in the waste treatment in the process-PC. In the process-PC+disp.C, a disposal process using a chelating agent is employed. In the process-PC+disp.Z, a "zero emission" type system boundary is assumed. In this method, waste is presumed to be dumped as a completely harmless material. We used references [1] [2] and statistics [3] to make inventories. Impacts of transportation in the system are not calculated, since it was reported that the amounts of CO_2 are less than 1 percent of that of the total process [4].

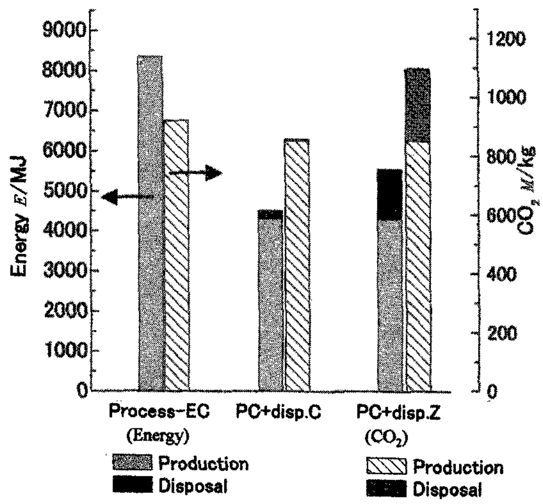


Figure 2 Results of LCA

Figure 2 shows the results of LCA. The energy consumption and CO_2 emission of ecocement production process are calculated 8342MJ/t-cement and 921kg-CO_2/t-cement respectively. On the other hand, in a process-PC+disp.C, they are 4507MJ/t-cement and 858kg-CO_2/t-cement. In the process-PC+disp.Z, they are 5554MJ/t-cement and 1095 kg-CO_2/t-cement.

In process-PC+disp.C, the environmental loads of waste disposal are underestimated, because the impact that will be caused by the discarded wastes are not calculated. They still have the potential to attack the environment, causing problems such as water pollution. So the advantage of ecocement production is not visible in the disp.C case. This problem is considerably solved by "zero emission" type system boundary. As shown in Figure 2, process-PC+disp.Z exceeds the CO_2 emission of process-EC. From the results of this analysis we can show the advantage of the "zero emission" type system boundary. However, the energy consumption of process-EC is larger than that of process-PC even in the disp.Z case. We will mention it in the discussion.

2.2 ExA (Exergy Analysis)

Exergy can be used as a measure of environmental impact, since it is considered that various kinds of pollution are essentially caused by high exergy materials [5] [6] [7]. This viewpoint was recently suggested by Ayres [5]. Exergy is defined as the maximum work that can be extracted from a given state during the change of the state to the standard point. If the wastes are disposed in the state of zero exergy, they do not give any impacts on the environments. Theoretically, however, it is difficult to define the standard point because the environment is not in a steady state and is different from place to place. We designate the zero point: in this study, 1atm, 25°C and assigned the exergy of most stable compound as zero based on JIS Z 9204 [8].

Exergy of a chemical compound can be expressed as follows:

$$E^x(A_aB_bC_c)=\Delta G_f(A_aB_bC_c)+aE^x(A)+bE^x(B)+cE^x(C)$$

where $E^x(A_aB_bC_c)$ is the exergy of the chemical compound of $A_aB_bC_c$, $\Delta G_f(A_aB_bC_c)$ is the free energy and $E^x(A)$, $E^x(B)$, $E^x(C)$ is the exergy of each element.

We count only chemical exergy here, since it is the main source of environmental damage. The exergy of heat and diffusion or mixture are ignored.

Figure 3 and Table I show the results of ExA. We evaluated the same system as LCA. In Figure 3, the length of the arrows represents the magnitude of exergy and the width of the mass of materials [6] [7]. The length of a side of the equilateral triangle expresses the total mass input of the process. The three sides of the equilateral triangle represent the resources, the products and the waste of the process, respectively. This diagram can depict both exergy and mass flow.

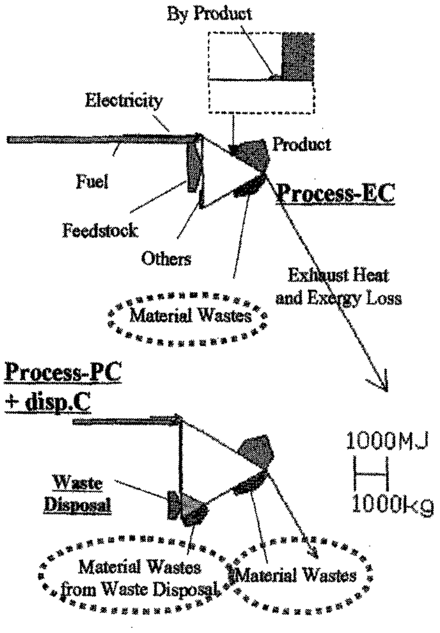


Figure 3 Results of Exergy Analysis

Using exergy as a measure of environmental impact, we can integrate the various kinds of impact into one indicator, exergy. In our study, we focused on chemical exergy of waste because chemically non-stable substances actually have important roles in the attack of environment. Exergy of material waste is shown in Table I. The exergy of material wastes emitted by process-EC is about half of process-PC+disp.C. In this study, however, some of the exergy of materials was not calculated because of lack of data. It is necessary to examine this result.

The result of disp.Z is interesting. We will discuss it later.

Table I Results of Exergy Analysis

	Process-EC		Process-PC+disp.C		Process-PC + disp.Z	
INPUT	M/kg	E^{x}/MJ	M/kg	E^{x}/MJ	M/kg	E^{x}/MJ
Limestone	827.61	8.26	1200.00	11.97	1200.00	11.97
Clay	-	-	232.00	27.56	232.00	27.56
Silica	-	-	38.00	0.15	38.00	0.15
Iron Slag	-	-	25.00	1.13	25.00	1.13
Gypsum	41.30	0.51	43.94	0.54	43.94	0.54
Incinerator Ash	613.50	434.62	460.12	261.50	460.12	261.50
Fly Ash	-	-	153.37	166.31	153.37	166.31
Water	-	-	178.83	0	7163.82	0
Chelating Agent	-	-	4.60	-	-	-
HCl	-	-	-	-	580.25	731.11
Zinc	-	-	-	-	8.84	45.64
Sodium Hydrate	-	-	-	-	102.76	259.50
Sulfuric Acid	-	-	-	-	0.05	0.12
Electricity	-	2382.53	-	999.18	-	1243.51
Fuel	141.86	5959.14	121.71	3351.11	121.18	3327.66
O_2	532.88	65.74	530.66	65.47	528.79	65.24
N_2	0.69	0.02	0.18	0.00	0.18	0.00
Total	2157.83	8850.82	2988.43	4884.93	10658.31	6141.95
OUTPUT	M/kg	E^{x}/MJ	M/kg	E^{x}/MJ	M/kg	E^{x}/MJ
Ecocement	1000.00	872.67	-	-	-	-
Cement	-	-	1000.00	878.81	1000.00	878.81
Kiln Dust	68.50	207.74	-	-	-	-
Landfilled Waste	-	-	796.93	**427.81**	108.68	**0.12**
Metal Content Residual	-	-	-	-	57.32	5.99
Waste Waster	-	-	-	-	8303.22	**257.34**
CO_2	825.81	**379.16**	816.81	**375.03**	815.21	**374.29**
SO_2	1.26	**6.06**	2.46	**11.83**	2.46	**11.81**
NO_2	2.26	**2.75**	0.60	**0.73**	0.59	**0.72**
H_2O	259.99	**0**	371.63	**0**	370.84	**0**
Exegry loss and exhaust heat	-	7382.45	-	3190.74	-	4612.88
Total	2157.83	8850.82	2988.43	4884.93	10658.31	6141.95
Total Exergy of Material Wastes		**387.96**		**815.39**		**644.27**

2.3 TMR (Total Materials Requirement)

The total amount of materials used in the process is considered to be one of the important indicators of the environmental impacts. TMR is defined as follows [9]:

$$
\begin{aligned}
(\mathrm{TMR}) &= \Sigma\ (\text{direct input materials}) \\
&\quad + \Sigma\ (\text{indirect input materials}) \\
&\quad + \Sigma\ (\text{hidden flows})
\end{aligned}
$$

" Direct input materials" and "indirect input materials" can be obtained from economic statistical data (such as I/O table). On the other hand, it is difficult to collect the data of hidden flows of materials, because we do not buy and sell these things. However, they consist of parts of materials movement, accompanied by direct and indirect input materials, such as rocks that come with mining and deforestation. "Hidden flows" also includes the materials that are used to keep scenery or to recover the water system.

Table II Results of TMR

	Material	TMR		
Process-EC	Flow t/t-cement	Mining t/t-materials	Disposal t/t-materials	Total t/t-cement
Input				
Limestone	0.83	**1.49**	(10.79)	1.24
Gypsum*	0.04	**1**	(693.65)	0.04
Incinerator Ash	0.61	**0**	(952.64)	0
Total	-	-	-	**1.28**
Output				
Ecocement	1.00	-	**390.07**	390.07
Total	-	-	-	**390.07**
Process-PC				
Input				
Limestone	1.20	**1.49**	(10.79)	1.79
Clay	0.23	**1.56**	(5.51)	0.36
Silica	0.04	**1.95**	(3.69)	0.07
Iron*	0.03	**1**	(18.35)	0.03
Gypsum*	0.04	**1**	(693.65)	0.04
Total	-	-	-	**2.30**
Output				
Cement	1.00	-	**43.47**	43.47
Incinerator Ash	0.61	(0)	**952.64**	584.44
Total	-	-	-	**627.92**

* There was not enough data to calculate TMR, so we assumed them to be 1.

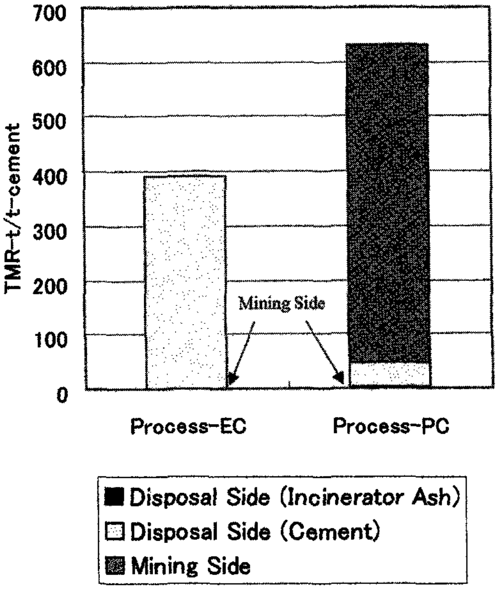


Figure 4 Results of TMR

On the basis of ore-TMR [9], we estimated the TMR of cement production. We presumed different accounting methods on the mining side and the disposal side. On the mining of natural resources side, the reciprocal number of the yield gives the value of TMR. In the disposal side, waste-TMR is defined as the amounts of substances that are necessary to dilute waste to the environmental level. The average composition of soil examined at various places in Japan [10] was set as the standard. In the Table II, the TMR of materials is shown. On the mining side, the TMR of incinerator ash is put as zero. Because ash is considered to already exist in the human society. We evaluated only feedstock. Fuel was not considered in this study. We did not consider waste treatment process, in this method, either.

Process-EC makes 1000kg ecocement as a product and uses 613kg incinerator ash, whereas process-PC makes 1000kg cement as a product. Then, for the comparison, we assumed that the incinerator ash that used in the process-EC is dumped directly into the environment, in process-PC.

Table II and Figure 4 shows the results of TMR. In the process-EC disposal side, heavy metals (kiln dust) are collected and sent to refinery. As shown in Figure 4, it decreases the TMR of process-EC. The decrease in the process-EC is about a third part of the TMR of process-PC.

3. DISCUSSION

3.1 "Zero Emission" Type System Boundary

Figure 5 shows the results of E^xA of waste disposal processes. Even in disp.Z case, waste materials have exergy. If the systems are truly "zero emission", exergy of the wastes should be zero. This means that the "zero emission" type system boundary is not complete and more processes are needed to change the waste to completely harmless compounds.

This argument is also supported by the energy consumption, analyzed in LCA. In our LCA, the energy consumption of process-EC is larger than that of process-PC even in the disp.Z case. There are several reasons. For example, the efficiency of the ecocement kiln is forced to be low because the formation of dioxins must be avoided. The recovering process of heavy metals is another cause. Both chlorine and heavy metals are contained in the incinerator ash. If there were less or no chlorine in the ash, the process would be changed and efficiency would be improved. On the other hand, more energy would be necessary to realize truly zero emission system. In such a case, the energy consumption of process-EC will become less than that of process-PC.

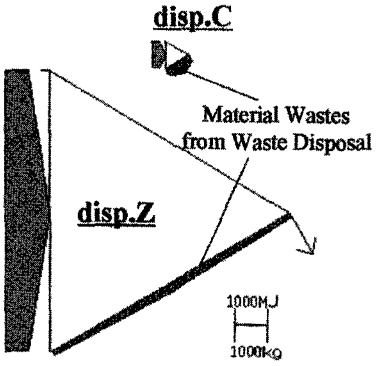


Figure 5 Exergy Analysis of Waste Disposal

3.2 TMR and E^xA

As shown in Table II, there are large differences between the TMR of mining and disposal. It is caused by the differences in definition as described in 2.3. In this treatment, the materials disturbed by mining, which cause soil and water pollution are not taken into account.

When we evaluate environmental impact, it is important that materials are chemically active or inactive. Chemically active materials cause environmental impact. In this study, this impact is evaluated by E^xA. Chemically inactive materials do not attack the environment themselves. However, the movement of inactive materials also causes environmental impact. This impact can be evaluated by TMR. Hence, we should use both E^xA and TMR and compare the results of these methods.

4. CONCLUSION

We evaluated the environmental impacts using three methods: LCA, E^xA and TMR.

(1) As shown in Figure 2, in our LCA, the loads of waste disposal process of process-PC+disp.C was underestimated. In process-PC+disp.Z, a "zero emission" type system boundary was employed to evaluate them. As the result, process-PC+disp.Z exceeded process-EC in the CO_2 emission.

(2) Exergy analysis evaluated the quality of waste materials and integrated the various kinds of impact into one indicator, exergy. The exergy of material wastes emitted by process-PC+disp.C was almost double that of process-EC.

(3) The decrement of TMR in the process-EC was about one third of TMR of process-PC.

Each of the methods has advantage and disadvantage and evaluates the different aspect of the environmental impact. We showed that it is important to evaluate environmental impact from various viewpoints. Not only LCA but also other new methods are necessary to develop the advanced evaluation methods for environmental impact.

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