Technical report

Inventory Data and Case Studies for Environmental Performance Evaluation of Concrete Structure Construction

Kenji Kawai[1], Takafumi Sugiyama[2], Koichi Kobayashi[3] and Susumu Sano[4]

Received 6 April 2005, accepted 17 August 2005

Abstract

This paper aims to provide common basis for the estimation of emission inventory data necessary for the evaluation of environmental impact of a concrete structure through its life cycle. Intensive literature survey and hearing to the institutes concerned have been deliberately conducted to collect relevant data to concrete materials, other materials involved, construction, demolition, and disposal and recycling. Consequently emission inventory data of CO_2, SO_x, NO_x, and particulate matter were able to be prepared in an objective way. In addition, fundamental inventory data of these emission gases and particulate matter were provided for various kinds of energy. Furthermore most commonly used machines, instruments and other equipments on concrete structure construction are presented and provided for their related inventory data. In this way, inventory data regarding 91 detail items in total were able to be provided. By using these inventory data, four case studies where environmental impact caused by the construction of concrete structures was considered as a performance parameter of the structures similarly to serviceability, safety, and durability of the structures were also investigated based on design methods proposed previously by the authors in order to confirm the applicability of these inventory data to environmental performance evaluation of concrete structures.

1. Introduction

The life cycle of concrete structures affects global and local environment in various aspects such as global warming, destruction of the ozone layer, consumption of natural and energy resources, reduction of forests, desertification, acidification, air, water, and soil pollutions, noise and vibration, changes of ecosystem in land and water, changes in landscape, waste emission, heat island, and so on. Toward the challenges of sustainable development, in order to prevent environmental destruction and to minimize environmental burdens, many types of countermeasures considering environmental impact reduction such as the uses of supplementary materials, industrial by-products and industrial wastes, recycling of concrete wastes, zero-emission activities in construction sites, and so on have been performed and developed in the concrete industry field (for example, Malhotra 2000; Péra and Ambroise 2000; Jahren 2004). Idealistically as many environmental aspects as possible should be evaluated when the environmental impact of the life cycle of concrete structures is considered as a performance parameter of the structures. But unfortunately environmental impact factors which can be quantified are limited for now. Sufficient data even regarding these limited factors have not been prepared.

When the effect of the action regarding environmental consciousness on the reduction of environmental impact is estimated, the life cycle assessment (LCA) is basically adopted. Also in case environmental performance of concrete structures is evaluated, the LCA method will be used for the estimation of environmental impact of concrete structure construction. The framework of the LCA is specified in ISO 14040 (1997). According to ISO 14040, life cycle assessment must include definition of goal and scope, inventory analysis, impact assessment, and interpretation of results, as illustrated in **Fig. 1**. The goal and scope of an LCA study must be clearly defined and consistent with the intended application. The scope should be sufficiently well defined to ensure that the breadth, the depth, and the detail of the study are com-

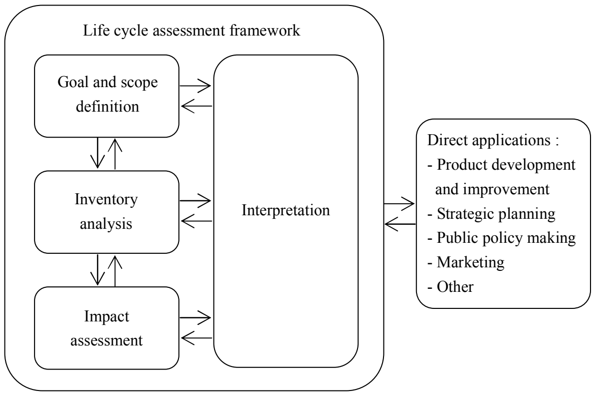


Fig. 1 Phase of an LCA.

[1]Associate Professor, Department of Social and Environmental Engineering, Hiroshima University, Japan.
E-mail: kkawai@hiroshima-u.ac.jp
[2]Associate Professor, Department of Civil Engineering, Gunma University, Japan.
[3]Lecturer, Department of Civil Engineering, Chubu University, Japan.
[4]Associate Research Scientist, Research & Development Center, Taiheiyo Cement Corporation, Japan.

patible and sufficient to address the stated goal. The inventory analysis involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system. The qualitative and quantitative data for inclusion in the inventory must be collected for each unit process that is included within the system boundaries. The impact assessment phase of LCA is aimed at evaluating the significance of potential environmental impacts using the results of the life cycle inventory (LCI) analysis. The interpretation is the phase of LCA in which the findings from the inventory analysis and the impact assessment are combined together, or, in the case of life cycle inventory studies, the findings of the inventory analysis only, consistent with the defined goal and scope in order to reach conclusions and recommendations.

For help to perform LCA, many kinds of tools has been developed and released to the public. These tools include inventory data for environmental impact which were researched and collected by the institutes concerned, but unfortunately most tools are not free and inventory data included in their tools are not usually opened. In order to introduce and promote environment-conscious design of concrete structures, the preparation of a set of free and reliable inventory data is needed. These inventories do not need to include goods and services that are not associated with concrete structure construction but to include details regarding concrete structure construction.

In this paper, intensive literature survey and hearing to the institutes concerned have been deliberately conducted to collect relevant data to concrete materials, other materials involved, construction, demolition, and disposal and recycling. Consequently emission inventory data of CO_2, SO_x, NO_x, and particulate matter were able to be prepared in an objective way. In addition, fundamental inventory data of these emission gases and particulate matter were provided for various kinds of energy such as electric power, LPG for fuel, LNG (imported), light oil, gasoline, heavy oil, kerosene, and acetylene gas. In this way the inventory data regarding 91 detail items in total were able to be provided. Through this inventory data collection, significance of compiling inventory data is also discussed with regard to quantitatively evaluating environmental impact of concrete structures.

Furthermore four case studies to which these inventory data are applied are investigated based on design method verifying environmental performance and design method considering environmental performance which were proposed by the authors in the previous paper (Kawai *et al*. 2005). In these case studies, environmental impact caused by concrete structure construction is considered as a performance parameter of the structure similar to serviceability, safety, and durability of the structure.

2. Inventory data collection

The collection method of inventory data includes an input-output analysis and a process analysis. In the input-output analysis, input-output tables showing the trading amounts of all of goods and services produced and consumed in a year in a country by section with a common unit (i.e. a monetary unit) are used, and direct and indirect input energy and environmental impact are calculated using investigated inventories between industries with a top-down processing. In this analysis, the direct and indirect inventory of a product can be theoretically calculated, but it is not suitable to an analysis of various products and technologies since the classification of section is rough and the evaluation is limited to the average of goods in a section. On the other hand, the process analysis is carried out with a bottom-up processing and the life cycle of a product is investigated in detail. In this analysis, the preparation basis of inventories is clear, while the coverage of processes which can be investigated is limited. In this paper, the collection of inventory data regarding the life cycle of concrete structures is carried out with the process analysis.

2.1 Energy and transportation

Inventory data of energy and transportation are used in common for concrete materials, construction works, demolition works, and disposal and recycling in this paper. This methodology to use common basis for energy and transportation is of great significance for the estimation of each inventory data regarding the life cycle of a concrete structure.

As for fuels, data for mining in a production country, transportation to Japan, refinement, and transportation to a final demand place were cited from Petroleum Energy Center, Japan (PEC 2002) and Plastic Waste Management Institute, Japan (PWMI 2001). Calorific values of fuels were referred to data in the Agency for Natural Resources and Energy, Japan (ANRE 2004). The values of CO_2 emission by combustion of fuels were based on the emission coefficients for 1999 published by the study group on the calculation methodology of the emissions of green house gases, Ministry of the Environment, Japan (MOE 2000). Regarding the use of light oil, sources were divided into moving emission sources such as trucks and stationary emission sources such as construction machines. The emissions of NO_x and particulate matter generated by the consumption of light oil in each source were obtained from the literature by Nanzai *et al.* (2002).

As for purchased power, the amount of CO_2 emission is an average of the total amount of CO_2 emitted from all of electric power companies in Japan in 2002 reported by the Federation of Electric Power Companies of Japan (FEPC 2004a). The amount of energy consumption is calculated on the basis of reported data by Petroleum Energy Center, Japan (PEC 2002) using the following equation.

$$(Energy\ consumption) = E_i \cdot E_0 / H_i$$

Where E_i is percentage composition of total primary energy supply by energy sources, E_0 is quantity of heat supplied at generation (= 9.00 MJ/kWh), and H_i is calorific value of energy sources.

The amounts of SO_x and NO_x emission are calculated by the amount of each emission per unit of electricity generated by thermal power and the ratio of thermal power relative to total electric power generation which were reported by the Federation of Electric Power Companies of Japan (FEPC 2004b). The emission amount of particulate matter was based on the paper reported by Matsuno *et al.* (1998).

In this way, as shown in **Table 1**, the emission inventory data of CO_2, SO_x, NO_x, and particulate matter were provided for various energy types such as electric power, LPG for fuel, LNG (imported), light oil, gasoline, heavy oil, kerosene, and acetylene gas.

Regarding transportation, energy consumption of each was calculated from the following equation.

$$(Fuel\ consumption) = \frac{(Engine\ power)\times(Specific\ fuel\ consumption)}{(Maxmum\ capacity)\times(Average\ speed)}$$

Where, average speed was assumed to be 30 km/h, and engine power and specific fuel consumption were obtained from the Equipment Cost Calculation Chart (JCMA 2001). The amounts of CO_2, SO_x, NO_x, and particulate matter emission to the air in motion were calculated by fuel consumption shown in the above equation and the inventory data shown in **Table 1**. Summarized data are shown in **Table 2**.

By using these common data, emission inventory data for construction machinery, instruments, and other equipments which will be used through the life cycle of

Table 1 Emission inventory data for energy used for operation.

	Unit (*)	Calorific value (MJ/*)	CO_2 emission (kg-CO_2/*)	SO_x emission (kg-SO_x/*)	NO_x emission (kg-NO_x/*)	Particulate matter emission (kg-PM/*)
Electricity	kWh	9.00	0.407	0.13×10^{-3}	0.16×10^{-3}	0.03×10^{-3}
LPG for fuel	kg	50.2	3.03	#	#	#
LNG (imported)	kg	54.5	2.79	(-)	(-)	(-)
Light oil	L	38.2	2.64	2.04×10^{-3}	19.77×10^{-3} *1 39.61×10^{-3} *2	1.66×10^{-3} *1 2.01×10^{-3} *2
Gasoline	L	34.6	2.31	0.59×10^{-3}	#	#
Heavy oil (Type A)	L	41.7	2.77	13.00×10^{-3}	# *1 2.38×10^{-3} *2	# *1 3.00×10^{-3} *2
Kerosene	L	36.7	2.50	(-)	(-)	(-)
Acetylene gas	m^3	50	3.38	(-)	(-)	(-)

Note that each entry does not include mining and subsequent transport of corresponding energy source.
#: Refer to the literature by Nanzai *et al.* (2002).
*1: Fuel consumption by driving a truck and other related vehicles on public road, which is considered a part of construction.
*2: Fuel consumption by operating machinery and equipment.
(-) indicates either no data available or additional survey needed for each particular case.

Table 2 Emission inventory data for transportation.

		Unit (*)	Input energy (GJ)	Oil conversion (kg)	Purchased power (kWh)	CO_2 emission (kg-CO_2/*)	SO_x emission (kg-SO_x/*)	NO_x emission (kg-NO_x/*)	Particulate matter emission (kg-PM/*)
Truck	Gasoline (2t)	km.t	0.00300	0.0770	-	0.200	0.0000600	0.000250	0.000250
	Diesel (2t)	km.t	0.00337	0.0756	-	0.233	0.000179	0.00174	0.000146
	Diesel (4t)	km.t	0.00222	0.0497	-	0.153	0.000118	0.00115	0.0000964
	Diesel (10t)	km.t	0.00177	0.0396	-	0.122	0.0000941	0.000914	0.0000768
	Diesel (20t)	km.t	0.00103	0.0231	-	0.0714	0.0000549	0.000534	0.0000448
Dump truck	Diesel (10t)	km.t	0.00169	0.0379	-	0.117	0.0000901	0.000875	0.0000735
Agitator truck *1	0.8-0.9m^3	km.m^3	0.00566	0.127	-	0.392	0.000302	0.00587	0.000298
	1.6-1.7m^3	km.m^3	0.00639	0.143	-	0.442	0.000340	0.00663	0.000336
	3.0-3.2m^3	km.m^3	0.00399	0.0896	-	0.276	0.000213	0.00414	0.000210
	4.4-4.5m^3	km.m^3	0.00366	0.0820	-	0.253	0.000195	0.00379	0.000192
Freight car *2		km.t	0.000507	-	0.0539	0.0219	0.00693	0.00844	0.00140
Ship *3	500t class	km.t	0.00277	0.0553	-	0.162	0.00280	0.00470	0.0000721
	1000t class	km.t	0.00170	0.0340	-	0.0999	0.00172	0.00289	0.0000444
	2000t class	km.t	0.00105	0.0209	-	0.0615	0.00106	0.00178	0.0000273
	5000t class	km.t	0.000552	0.0110	-	0.0324	0.000559	0.000937	0.0000144
	10000t class	km.t	0.000340	0.00679	-	0.0199	0.000344	0.000577	0.00000886

*1: Type of energy: Light oil
*2: Type of energy: Electric power
*3: Type of energy: Heavy oil type A

concrete structures in material productions, construction, demolition, and disposal and recycling can be estimated.

2.2 Materials

Emission inventory data for portland cement, blast furnace slag cement and fly ash cement are the sum of the inventory data as of 2003 reported by Japan Cement Association and corresponding emission data derived from the transportation of raw materials and the use of purchased power. The data of the uses of fuels, power, resources, and wastes and CO_2 emission for ecocement were referred to the previous studies (JSCE 2002). The emissions of SO_x, NO_x, and particulate matter for ecocement are the sum of these data supplied by its manufacturing company and other emission data derived from the use of purchased power. Ecocement was developed in Japan in terms of measures for reduction of environmental impact. About 50 % of its raw materials are wastes including incinerator ash. This cement consists of the same main mineral components as normal portland cement (Shimoda and Yokoyama 1999).

The amount of energy consumption during grinding process for manufacturing natural aggregate and lime stone aggregate was calculated by the Bond method (JCMA 1975). In addition, related energy at the collection of lime stone for the ceramics whose data is available from Japan Cement Association was added. Then the total energy for these aggregates was calculated by further adding the energy related to electricity for sieving and to transportation within a production site. The amount of energy consumption for melting slag aggregate using municipal waste was calculated on the basis of a calculation software (HOK 1998). Note that the calculation domain ranged from generation of sintered ash of municipal waste to manufacture of melting slag aggregate.

Among emission inventory data for aggregates and mineral admixtures, the emissions of SO_x, NO_x, and particulate matter derived from their manufactures could not be collected and the emissions derived from electric power only were considered. Accordingly these emission inventory data should have been estimated very small. Waste aggregates are produced using incinerated ashes of municipal wastes as a primary raw material like the ecocement. The emission inventory data of SO_x, NO_x, and particulate matter for these waste aggregates of both melted using fuel type and electrical type were estimated small because the emission data regarding to environmental impact during the manufacturing processes are not included in this estimation.

Energy directly consumed during grinding for manufacturing blast furnace slag is electricity. In this paper, the amount of energy for manufacturing blast furnace slag with a specific surface area of 4400 cm^2/g by blain was calculated using reported inventory data on electricity for its grinding (Uchida 1991). The amount of electricity consumed during grinding process of fly ash was collected from reported data (Tamashige *et al.* 1992). For lime stone powder, energy used for the collection was added to energy used for coarse and fine grindings using reported calculation method (Sano *et al.* 2000).

Mineral admixtures such as blast furnace slag and fly ash are manufactured products and hence traded as valuables. However since mineral admixtures are by-products, the emission inventory data for these materials are generally estimated using only consumption of energy necessary for their processing. For example, the process of blast furnace slag requires energy as electric power to crush. In this way, other environmental impacts during the manufacturing stage for these by-products are not taken into account in this paper.

The amounts of CO_2, SO_x, and NO_x emission during steel manufacturing processes were investigated using a reference (Ishikawa *et al.* 1999). Then emission inventory data for steel materials were estimated using the amount of these emitted gases and the necessary amount of electric power consumption for the manufactures. In fact regarding steel materials, very few information on emission inventory data can be obtained as for now. This is especially true for electric furnace steel that is mainly used as reinforcing bars nowadays. Under these circumstances, emission inventory data for electric furnace steel and basic oxygen furnace steel were estimated using a little information available. Estimation of the emission of particulate matter of each steel was based on only the source of electric power consumption because of no information.

2.3 Construction works

Emission inventory data for construction were estimated on the basis of manufacturing concrete and running construction machinery, instruments, and other equipments. Emission inventory data for manufacturing concrete in a concrete plant was calculated with the amount of electric power consumption for mixing concrete except for SO_x, NO_x, and particulate matter emissions which were obtained from emission inventory data for stationary emission sources of construction machines and the amount of light oil consumption.

Construction for concrete structures is normally encountered by mixing, transportation, and placement of fresh concrete followed by consolidation and curing. During these works, concrete mixers, agitator trucks, concrete pumps, vibrators, and heaters will be employed. Steam curing and autoclave curing will be used for factory products. In addition, crawler cranes, truck cranes, and wheel cranes will be needed on a construction site. Furthermore diesel generators will be necessary. In this way, construction machinery, instruments, and other equipments are diverse on the concrete structure construction. In this paper, most commonly used machines for the construction are presented and provided for their related inventory data. Where, energy needed by autoclave curing was empirically assumed to 1.2 times than that needed by steam curing. In the calculation for construction machines, engine power of each machine

(JCMA 2001) and light oil consumption per power were used. For NO_x emission of construction machines, the adoption of exhaust emission measures was considered. Based on the trend of Japan's regulation values concerning measures to reduce automobile exhaust gas (MOE 2003), the emission of a machine adopting the measures was estimated to be 70 % of the emission of a machine without measures.

Emissions of CO_2, SO_x, NO_x, and particulate matter were estimated according to **Table 1** depending on the kinds of energy and their amount consumed as well as the magnitude of construction methods concerned.

2.4 Demolition works

Emission inventory data of demolition works were estimated on the basis of the amount of fuel consumption by machinery used and classified for kinds of concrete structures to be demolished. Light oil and acetylene gas are normally used for the running of machinery such as breaker, welding machine, and crawler crane. Then the amount of these fuels consumed resulted in taking responsibility for the estimation of the emission inventory data of demolition work in this paper. In addition, according to the magnitude of concrete members and structures to be demolished, the amount of fuel consumption necessary for the corresponding demolition works will be varied. Therefore the emission inventory data were prepared depending on the magnitude and kinds of concrete structures under consideration. Types of machinery and the magnitude of concrete members and structures that can be commonly employed and represented in a demolition work were assumed using the data issued by Construction Research Institute (CRI 1998). Emissions of CO_2, SO_x , NO_x, and particulate matter were estimated according to **Table 1** depending on the kinds of energy and the magnitude of demolition work concerned.

2.5 Disposal and recycling

Emission inventory data of disposal and recycling were estimated on the basis of the amount of consumed energy such as electric power, light oil, heavy oil, and kerosene, which were normally used to run a correspond machinery and instruments for these operations. Emissions of CO_2, SO_x, NO_x, and particulate matter were estimated according to **Table 1** for kinds of energy concerned.

(1) Disposal

Operation of the disposal of concrete pieces, metals, and others involved can be classified in leachate-controlled type and not-leachate-controlled type within a landfill site for industrial waste. In this paper, the landfill operation and its management were assumed to be conducted similar to the case of general waste materials. Then the amounts of electric power, light oil, heavy oil, and kerosene consumed for the landfill operation were cited from the University report (HOK 1988).

(2) Recycling

Emission inventory data of recycling are expressed as per 1 ton of concrete waste that is treated for recycled aggregates. Note to convert into the unit of per 1 ton of recycled aggregates if necessary. With a self-mobile recycling machine used on site, Type III recycled coarse aggregate and equivalent Type II recycled fine aggregate are produced. These recycled aggregates are mostly employed as roadbed materials and filling materials. Data regarding kinds of energy and necessary amount of running the recycling machine were collected by a hearing from practicians. The amount of light oil used up for the recycling includes the amount of light oil for running heavy machines to transport and throw concrete pieces into the recycling machine within site.

Recycled aggregates which are treated outside site include Type I recycled coarse aggregates and Type I intensely recycled fine and coarse aggregates that are highly treated with heating and grinding methods. Kinds of energy and its amount for both Type I recycled aggregates were obtained through literature survey (CRR 1997, Shima *et al.* 2001, Mitsubishi Materials 2001).

3. Inventory data

3.1 Emission inventory data for materials

As a result of intensive survey and hearing to relevant institutes, estimated emission inventory data for materials are given in **Table 3**. During a process of this research, inventory data on non-metal mineral, iron resource, material recycling and waste emission were also collected and hence are shown in **Table 3** as well as CO_2, SO_x, NO_x, and particulate matter emission inventory data. Especially the material recycling is a positive impact on environment where waste materials from other industries can be effectively utilized for manufacturing cement and aggregates.

$$\begin{pmatrix} EID_{CO_2} \\ EID_{SO_x} \\ EID_{NO_x} \\ EID_{PM} \end{pmatrix} = \begin{pmatrix} 0.407 & 3.53 & 3.32 & 2.82 & 2.67 & 3.01 & 2.65 & 3.38 \\ 0.13\times10^{-3} & 3.04\times10^{-3} & 0.78\times10^{-3} & 3.59\times10^{-3} & 2.31\times10^{-3} & 14.67\times10^{-3} & 1.53\times10^{-3} & 0 \\ 0.16\times10^{-3} & 2.27\times10^{-3} & 1.07\times10^{-3} & 60.53\times10^{-3} & 1.29\times10^{-3} & 3.64\times10^{-3} & 1.13\times10^{-3} & 0 \\ 0.03\times10^{-3} & 0 & 0 & 3.67\times10^{-3} & 0 & 3.0\times10^{-3} & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} EL \\ LPG \\ LNG \\ L.O. \\ G.S. \\ H.O. \\ K.R. \\ A.G. \end{pmatrix} \quad (1)$$

Table 3 Emission inventory data (Materials).

		Unit (*)	Type of energy *1 (main use)	Input energy *2 (GJ/*)	Oil conversion (kg)	Coal conversion (kg)	Purchased power (kWh)	Non-metal mineral (kg)	Iron resource (kg)	Material recycling (wet-kg)	Waste emission (wet-kg)	CO_2 emission (kg-CO_2/*)	SO_x emission (kg-SO_x/*)	NO_x emission (kg-NO_x/*)	Particulate matter emission (kg-PM/*)
Cement	Normal portland cement	t	C, Oc, Hc, E	3.40	16.24	93.84	31.2	1 236	-	148	-	766.6	0.122	1.55	0.0358
	Blast furnace slag cement (Type B)	t	C, Oc, Hc, E	2.28	13.13	56.80	30.1	715	-	85	-	458.7	0.0809	0.919	0.0218
	Fly ash cement (Type B)	t	C, Oc, Hc, E	3.02	18.25	75.71	34.0	998	-	120	-	624.0	0.0984	1.25	0.0289
	Normal eco-cement	t	Ha, E	6.40	108.67	-	250.9	829	-	765	-	784.0	0.152	0.319	0.00652
Aggregate	Coarse aggregate (Natural, crashed)	t	L, E	0.05	0.37	-	4.3	1 000	-	0	-	2.9	*0.00607*	*0.00415*	*0.00141*
	Fine aggregate (Natural, crashed)	t	L, E	0.07	0.37	-	6.2	1 000	-	0	-	3.7	*0.00860*	*0.00586*	*0.00199*
	Limestone aggregate	t	L, E	0.05	0.37	-	4.3	1 000	-	0	-	2.9	*0.00607*	*0.00415*	*0.00141*
	Waste aggregate (Melted using fuel)	t	K, E	29.71	721.86	-	240.0	-	-	1 238	141	2 293.6	*0.0309*	*0.0376*	*0.00624*
	Waste aggregate (Melted electronically)	t	E	9.13	13.09	-	959.3	-	-	1 238	141	430.3	*0.123*	*0.150*	*0.0249*
	Recycled aggregate (Type III)	t	E	0.06	0.21	-	5.9	-	-	1 000	No data	3.1	*0.00127*	*0.0108*	*0.000655*
	Recycled aggregate (Type I)	t	E	0.38	0.49	-	39.8	-	-	1 000	No data	17.7	*0.00628*	*0.0289*	*0.00218*
Mineral admixture	Blast furnace slag	t	E	0.58	-	-	65.0	-	-	0	No data	26.5	*0.00836*	*0.0102*	*0.00169*
	Fly ash	t	E	0.43	-	-	48.2	-	-	0	No data	19.6	*0.00620*	*0.00754*	*0.00125*
	Limestone powder	t	L, E	0.35	0.37	-	36.8	1 000	-	0	No data	16.1	*0.0112*	*0.0103*	*0.00244*
	Coal ash	t	-	-	-	-	-	-	-	1 000	-	-	-	-	-
Steel	Electric furnace steel	t	E	4.24	3.60	71.79	337.7	33	93	No data	7	767.4	0.134	0.124	0.0101
	Basic oxygen furnace steel (Shapes)	t	Cc, C, E	18.54	7.29	728.45	260.5	65	1028	No data	7	1 256.0	1.18	1.80	0.00781
	Basic oxygen furnace steel (Bars)	t	Cc, C, E	18.40	7.29	728.45	253.2	65	1028	No data	7	1 213.0	1.18	1.80	0.00759
	Basic oxygen furnace steel (Wire rods)	t	Cc, C, E	18.98	7.29	728.45	299.4	65	1028	No data	7	1 321.8	1.18	1.81	0.00898

Note : The values written in italics include only emissions derived from electric power. Because of no data, the emissions derived from manufacturing processes are not considered.

*1: Type of energy: C=Coal, Cc=Coke, Oc=Oil coke, Hc=Heavy oil type C, Ha=Heavy oil type A, L=Light oil, K=Kerosene, E=Electricity.

*2: Conversion into calorific value.

3.2 Emission inventory data for construction, demolition, and disposal and recycling

Emission inventory data of CO_2, SO_x, NO_x, and particulate matter are estimated for a particular item concerned in construction, demolition works, and disposal and recycling using following Eq. 1. Where EID_{CO2} is CO_2 emission inventory data with a unit of kg-CO_2/*, EID_{SOx} is SO_x emission inventory data with a unit of kg-SO_x/*, EID_{NOx} is NO_x emission inventory data with a unit of kg-NO_x/*, and EID_{PM} is particulate matter emission inventory data with a unit of kg-PM/*. Note that the unit symbol (*) is either ton or hour or m^3 depending on the item under consideration. The values of *EL*, *LPG*, *LNG*, *L.O.*, *G.S.*, *H.O.*, *K.R.*, and *A.G.* are the amounts of electricity (purchased power), LPG for fuel, LNG (imported), light oil, gasoline, heavy oil, kerosene, and acetylene gas, respectively, which are used up for correspond machinery or instrument.

In Eq. 1 each entry in the 4 x 8 matrix includes both energy for mining and subsequent transport of corresponding energy source to Japan and energy for operation of related machinery and running vehicles. In the matrix, zero entry indicates no data available and hence was inserted for convenience. Each entry can be replaced according to future modification of related inventory data. Inventory data for energy that is only related to operation is given in **Table 1**. However the amounts of emission gases in the process of fuel combustion can vary where well-equipped facilities and machineries can emit less gases than that by poor-equipped ones. Therefore no entry for some data in **Table 1** must be appropriately determined according to its operational condition.

Table 4 Emission inventory data (Construction).

		Unit (*)	Energy (Fuel) type *1	Input energy *2 (GJ/*)	Oil conversion (kg)	Natural gas (kg)	Purchased power (kWh)	CO_2 emission (kg-CO_2/*)	SO_x emission (kg-SO_x/*)	NO_x emission (kg-NO_x/*)	Particulate matter emission (kg-PM/*)
Ready mixed concrete	Concrete plant	t	L,LNG, E	0.115	2.13	0.32	0.64	7.7	0.00342	0.0651	0.00331
	Concrete mixer (1.5m^3)	m^3	E	0.0163	-	-	1.81	0.7	0.000235	0.000289	0.0000542
	Concrete mixer (1.75m^3)	m^3	E	0.0166	-	-	18.5	0.7	0.000240	0.000295	0.0000554
	Concrete mixer (2.5m^3)	m^3	E	0.0135	-	-	1.50	0.6	0.000195	0.000240	0.0000450
	Concrete mixer (3.0m^3)	m^3	E	0.0138	-	-	1.53	0.6	0.000199	0.000244	0.0000458
Concrete placing	Agitator truck (0.8-0.9m^3)	h	L	0.144	3.24	-	-	10.0	0.00769	0.0747	0.00628
	Agitator truck (1.6-1.7m^3)	h	L	0.316	7.10	-	-	21.9	0.0169	0.164	0.0138
	Agitator truck (3.0-3.2m^3)	h	L	0.371	8.33	-	-	25.7	0.0198	0.192	0.0161
	Agitator truck (4.4-4.5m^3)	h	L	0.488	10.95	-	-	33.8	0.0260	0.253	0.0212
	Boom pump (40-45m^3/h)	m^3	L	0.00891	0.20	-	-	0.6	0.000475	0.00924	0.000468
	Boom pump (90-110m^3/h)	m^3	L	0.00639	0.14	-	-	0.4	0.000340	0.00662	0.000336
	Truck mounted concrete pump (40-45m^3/h)	m^3	L	0.00619	0.14	-	-	0.4	0.000330	0.00642	0.000325
	Truck mounted concrete pump (90-100m^3/h)	m^3	L	0.00476	0.11	-	-	0.3	0.000254	0.00494	0.000250
	Concrete pump (95-110m^3/h)	m^3	E	0.00457	-	-	0.51	0.2	0.0000660	0.0000813	0.0000152
Compaction	Flexible shaft vibrator (Electric, 60-70mm)	h	E	0.00535	-	-	0.59	0.2	0.0000772	0.0000950	0.0000178
	Form vibrator (0.1kW)	h	E	0.000486	-	-	0.05	0.0	7.02×10^{-6}	8.64×10^{-6}	1.62×10^{-6}
	Direct drive surface vibrato (Compaction width : 1.2m)	h	G	0.0432	0.97	-	-	2.9	6.05×10^{-7}	0.0000177	6.56×10^{-7}
Curing	Steam curing	m^3	E, Ha	0.593	9.91	-	10.35	38.5	0.0241	0.0317	0.0348
	Autoclave curing	m^3	E, Ha	0.712	11.89	-	12.42	46.2	0.0289	0.0381	0.0417
	Jet heater	h	K	0.160	3.30	-	-	10.7	0.000460	0.00720	0.0120
	Normal curing	h	-	0	-	-	-	0.0	0	0	0
Excavator	0.6m^3	h	L	0.747	16.75	-	-	51.7	0.0398	0.774	0.0393
	0.6m^3 (Adopted exhaust emission measures)	h	L	0.747	16.75	-	-	51.7	0.0398	0.542	0.0393

*1: Type of energy: G=Gasoline, Ha=Heavy oil type A, L=Light oil, K=Kerosene, E=Electricity.
*2: Conversion into calorific value.

Results of the estimation of the emission inventory data regarding the use of construction machinery, instruments, and other equipments that are normally employed for construction, demolishment, and disposal and recycling are shown in **Tables 4** to **5**, **Table 6**, and **Table 7**, respectively. In each table, necessary input energy for corresponding machinery and instruments that is given by conversion into calorific value is also provided. In the case of single fuel type used, each emission inventory datum is relatively easily calculated by the determination of the amount of fuel consumption with the calorific value. On the other hand for the case of several fuels needed for each machinery and instrument, the amount of respective fuel type must be determined, which is sometimes difficult. Then conversion into calorific value can be useful for estimating each emission inventory datum.

The emission inventory data shown in each table were calculated on an operational basis relevant to construction, demolition, and disposal and recycling, which means that input energy for mining and subsequent transport of each energy source to Japan was excluded. This was obtained by replacement of the 4 x 8 matrix in Eq. 1 with each entry given in **Table 1**.

4. Case studies

In order to promote the motions toward environmental impact reduction in concrete industries, concrete structure design method itself should be changed from current design method to environment-conscious design method. In the previous paper, design methods considering environmental impact through the life of a concrete structure as a performance parameter of the structure and an integrated evaluation method of environmental impact of a concrete structure connected with the costs of construction, maintenance, demolition, and recycling of that structure were proposed (Kawai *et al.* 2005).

In that paper, two types of concrete structure design methods that are design method verifying environmental performance and design method considering environmental performance were proposed. In design method

Table 5 Emission inventory data (Construction, continued).

		Unit (*)	Energy (Fuel) type	Input energy *1 (MJ/*)	Oil conversion (kg)	Natural gas (kg)	Purchased power (kWh)	CO_2 emission (kg-CO_2/*)	SO_x emission (kg-SO_x/*)	NO_x emission (kg-NO_x/*)	Particulate matter emission (kg-PM/*)
Crawler crane	Mechanical, 16t capacity	h	L	0.258	5.78	-	-	17.8	0.0137	0.267	0.0135
	Mechanical, 25-27t capacity	h	L	0.308	6.92	-	-	21.3	0.0164	0.320	0.0162
	Hydraulic, 4.9t capacity	h	L	0.196	4.40	-	-	13.6	0.0104	0.203	0.0103
Truck crane	Hydraulic, 11t capacity	h	L	0.204	4.58	-	-	14.1	0.0109	0.106	0.00889
	Hydraulic, 16t capacity	h	L	0.239	5.36	-	-	16.5	0.0127	0.124	0.0104
	Hydraulic, 22t capacity	h	L	0.246	5.53	-	-	17.1	0.0131	0.127	0.0107
Wheel crane	4.8t capacity	h	L	0.417	9.36	-	-	28.9	0.0222	0.433	0.0219
	15t capacity	h	L	0.457	10.26	-	-	31.6	0.0244	0.474	0.0240
	25t capacity	h	L	0.774	17.37	-	-	53.6	0.0412	0.803	0.0407
	5t (Adopted exhaust emission measures)	h	L	0.417	9.36	-	-	28.9	0.0222	0.303	0.0219
	16t (Adopted exhaust emission measures)	h	L	0.562	12.60	-	-	38.9	0.0299	0.408	0.0295
	25t (Adopted exhaust emission measures)	h	L	0.774	17.37	-	-	53.6	0.0412	0.562	0.0407
Motor grader	Blade length: 3.1m	h	L	0.357	8.01	-	-	24.7	0.0190	0.370	0.0188
	3.1m (Adopted exhaust emission measures)	h	L	0.357	8.01	-	-	24.7	0.0190	0.259	0.0188
Road roller	10-12t capacity	h	L	0.257	5.76	-	-	17.8	0.0137	0.266	0.0135
	10-12t (Adopted exhaust emission measures)	h	L	0.257	5.76	-	-	17.8	0.0137	0.186	0.0135
Tire roller	8-20t capacity	h	L	0.277	6.21	-	-	19.1	0.0147	0.287	0.0145
	8-20t (Adopted exhaust emission measures)	h	L	0.277	6.21	-	-	19.1	0.0147	0.201	0.0145
Tamper	60-100kg capacity	h	G	0.0322	0.72	-	-	2.1	4.51×10^{-7}	0.0000132	4.89×10^{-7}
Sprinkler	5500-6500L	h	L	0.207	4.64	-	-	14.3	0.0110	0.107	0.00899
Diesel generator	10kVA (Adopted exhaust emission measures)	h	L	0.0859	1.93	-	-	5.9	0.00458	0.0624	0.00452
	45kVA (Adopted exhaust emission measures)	h	L	0.278	6.23	-	-	19.2	0.0148	0.201	0.0146
	75kVA (Adopted exhaust emission measures)	h	L	0.456	10.23	-	-	31.6	0.0243	0.331	0.0240

*1: Type of energy: G=Gasoline, L=Light oil.
*2: Conversion into calorific value.

verifying environmental performance, environmental impact, including its reduction, caused by the construction of a concrete structure is considered as a performance parameter of the concrete structure. The verification and inspection of environmental performance in planning stages are performed as well as other performances such as serviceability, safety, and durability of the concrete structure. The quantitative value of the environmental performance will be set up by a decision maker. But actually it is not so easy to decide values for environmental performance of a concrete structure and to have a system where the inspection is carried out by a third party after the verification. Then in design method considering environmental performance, qualitative requirement for environmental performance can be evaluated. The evaluation of environmental performance is carried out by either verification or selection. In both verification and selection, multiple environmental impact factors can be integrated. Verification is prepared for quantitative requirement of environmental performance, while selection is prepared for qualitative requirement of environmental performance. In selection, environmental impact is quantitatively evaluated and the results of a cost survey for the construction of the concrete structure are specifically considered when qualitative requirement of environmental performance is evaluated.

In this chapter, the applicability of design methods described in the previous paper and the possibility of environment-conscious design of a concrete structure are investigated through case studies using a set of inventory data prepared in the previous chapter.

4.1 General

Four different case studies were carried out here. The structures studied are a prestressed concrete bridge, an overflow dike of a dam, a retaining wall, and a secondary lining in a tunnel. The effectiveness of design method verifying environmental performance was investigated in

Table 6 Emission inventory data (Demolition).

		Unit (*)	Energy (Fuel) type*1	Input energy *2 (GJ/*)	Oil conversion (kg)	CO_2 emission ($kg\text{-}CO_2$/*)	SO_x emission ($kg\text{-}SO_x$/*)	NO_x emission ($kg\text{-}NO_x$/*)	Particulate matter emission (kg-PM/*)
PC & RC	Demolished from the ground	m^3	L	0.225	5.06	15.6	0.0120	0.234	0.0118
	Demolished from the roof	m^3	L	0.149	3.34	10.3	0.00794	0.154	0.00783
	Underground	m^3	L	0.275	6.17	19.0	0.0147	0.285	0.0145
	Footing beam	m^3	L	0.340	7.63	23.5	0.0181	0.353	0.0179
	Foundation	m^3	L	0.371	8.31	25.6	0.0197	0.384	0.0195
SRC	Demolished from the ground	m^3	L	0.294	6.60	20.4	0.0157	0.305	0.0155
	Demolished from the roof	m^3	L	0.195	4.37	13.5	0.0104	0.202	0.0102
	Underground	m^3	L	0.351	7.88	24.3	0.0187	0.364	0.0185
Earth floor		m^3	L	0.160	3.60	11.1	0.00855	0.166	0.00843
Plane concrete	Less than 0.2m thickness	m^3	L	0.0917	2.06	6.3	0.00488	0.0951	0.00482
	More than 0.2m thickness	m^3	L	0.134	3.00	9.3	0.00712	0.139	0.00703
Tunnel		m^3	L	0.118	2.66	8.2	0.00631	0.123	0.00622
Pavement	Concrete pavement	m^3	L	0.130	2.91	9.0	0.00692	0.135	0.00683
Steel cut	Welding machine	m^3	A	0.0110	0.25	0.7	0	0	0
Steel frame cut	Crawler crane, welding machine	t	L, A	0.102	2.28	7.0	0.00488	0.0951	0.00482
Operation	Piling and loading	m^3	L	0.225	2.57	7.9	0.00611	0.119	0.00602
Breaker	Hydraulic, 600-800kg capacity	h	L	0.431	9.67	29.8	0.0230	0.447	0.0226
	Hydraulic, 1300kg capacity	h	L	0.747	16.75	51.7	0.0398	0.774	0.0393

*1: Type of energy: L=Light oil, A=Acetylene gas
*2: Conversion into calorific value

Table 7 Emission inventory data (Disposal and recycling).

		Unit (*)	Energy (Fuel) type *1	Input energy *2 (GJ/*)	Oil conversion (kg)	Purchased power (kWh)	Waste emission (wet-kg)	CO_2 emission ($kg\text{-}CO_2$/*)	SO_x emission ($kg\text{-}SO_x$/*)	NO_x emission ($kg\text{-}NO_x$/*)	Particulate matter emission (kg-PM/*)
Landfill site for wastes	Leachate-controlled type	t	L	0.0568	0.72	2.72	1 000	3.3	0.00447	0.0255	0.00198
			E	0.0237							
			Ha	0.0226							
	Non-leachate-controlled type	t	L	0.0186	0.53	-	1 000	1.6	0.00126	0.0246	0.00124
Recycled aggregate	Type III, 14-30t/h, treated in situ	t	L	0.0175	0.51	-	-	1.6	0.00120	0.0164	0.00119
	Type III, 35-85t/h, treated in situ	t	L	0.0501	0.42	-	-	1.3	0.000993	0.0135	0.000980
	Type III, 47-100t/h, treated in situ	t	K	0.133	0.39	-	-	1.2	0.000934	0.0127	0.000922
	Type III, 30t/h, treated outside the site	t	E *3	0.617	0.17	4.72	No data	2.3	0.00101	0.00866	0.000524
			L	0.0568							
	Type I	t	E	0.0237	0.17	13.92	No data	5.7	0.00220	0.0101	0.000763
			L	0.0226							
	Type I, Heating and grinding method	t	K	0.0186	8.68	29.00	No data	43.6	0.0165	0.139	0.00624
			E	0.0175							

Note: Unit: L/t for light oil, heavy oil, and kerosene, kWh/t for power.
*1: Type of energy: E: Purchased power, L: Light oil, Ha: Heavy oil type A, K: Kerosene.
*2: Conversion into calorific value.
*3: Power used up for jaw crasher (3.00 kWh/t), impact crasher (1.23 kWh/t), sieving (0.25 kWh/t), and transport (1.47 kWh/t).

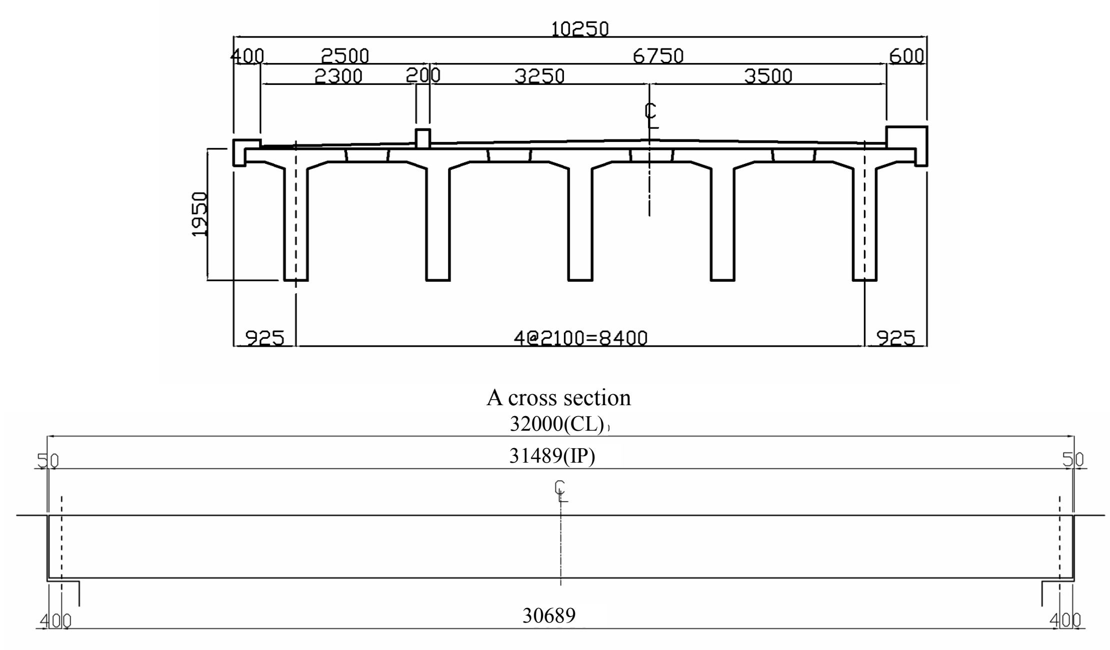
the case study of a PC bridge and the effectiveness of design method considering environmental performance was investigated in other three case studies.

4.2 Prestressed concrete bridge

A prestressed concrete simple girder bridge with T-section by the post-tensioning system (highway bridge, span: 32.000 m, width: 6.750 m for road and 2.500 m for pavement) was studied (JSCE 2002; Kawai 2002; Kawai and Sugiyama 2003). The overview of this structure is shown in **Fig. 2**. The girders of the bridge were manufactured in situ using ready-mixed concrete.

The conditions of the assessment for environmental performance in design method verifying environmental performance were assumed to be as shown in **Table 8**.

Since this structure was actually constructed, the



A cross section

A side view

Fig. 2 Schematic view of a prestressed concrete bridge studied.

Table 8 Assumed conditions in the case study of a PC bridge.

Purpose	Reduction of environmental impact on construction of the structure as much as possible
Range	Environmental impact of the manufacturing stage of materials and construction stage of the structure
Subject	Energy consumption and carbon dioxide emission
Criterion	5% reduction of carbon dioxide emission compared with a standard or conventional method

Table 9 Mix proportions and total amounts of ready-mixed concrete (PC bridge).

Type	Unit content (kg/m^3)						Amount (kg)					
	HC	BB	W	S	G	Ad.	HC	BB	W	S	G	Ad.
40-8-20 (H)	510	-----	181	575	1046	2.767	76 806	-----	27 259	86 595	157 528	416.7
30-8-20 (H)	394	-----	173	714	1019	2.137	16 745	-----	7 353	30 345	43 308	90.8
21-8-20 (BB)	-----	270	162	837	1017	1.465	-----	4 563	2 738	14 145	17 187	24.8
18-8-20 (BB)	-----	254	165	866	992	1.378	-----	7 010	4 554	23 902	27 379	38.0
Total	-----	-----	-----	-----	-----	-----	93 551	11 573	41 903	154 987	245 402	570.3

*) HC: High strength portland cement, BB: Blast furnace slag cement (Type B)

Table 10 Environmental impact in manufacturing stage (PC bridge).

	Amount (t)	Energy consumption (GJ)	CO_2 emission (kg-CO_2)
High strength portland cement	93.6	383.8	70 846
Blast furnace slag cement (Type B)	11.6	32.5	5 324
Sand	155.0	11.9	543
Gravel	245.4	14.5	687
Production process of ready-mixed concrete	548.0	63.0	4 209
Steel bars	24.5	638.3	41 745
PC wires	7.8	148.0	10 230
Total		1 292.0	133 584

written records of construction works for this structure were collected and a hearing from the construction company was carried out to obtain the details of construction works such as operation times and days of heavy machines. Although in actual construction the amounts of materials and machines used for construction are estimated in advance and the verification is performed in the planning stage based on this estimation, in this case study the collected data are assumed to be estimated data.

In construction, ready-mixed concrete was transferred and placed in situ. Concrete containing high strength portland cement with a nominal strength of 40 N/mm^2 is used for main girders and concretes containing high

Table 11 Suppliers of construction materials (PC bridge).

Material	Unit	Amount	Transportation method	Number of truck used	Distance from supplier to the site (km)	Total transportation distance (km.truck)
Ready-mixed concrete	m^3	240.4	Agitator truck (4.5m^3)	57	15	1 710
Frames	t	8.2	Truck (10t)	1	50	100
Steel bars (D16, D19 and D22)	kg	26 674.1	Truck (10t)	3	110	660
Steel bars (D10 and D13)	kg	7 821.0	Truck (10t)	1	80	160
PC wires	kg	7 754.9	Truck (10t)	1	260	520
Portal crane and erection girder			Truck (10t)	5	50	500
Sheaths	kg	613.6	Truck (4t) x 0.15	1	320	96
Rubber supports and rubber joints	kg	166.2	Truck (4t) x 0.04	1	550	44
Drain devices	kg	218.8	Truck (4t) x 0.05	1	90	9
Unseating prevention devices	kg	830	Truck (4t) x 0.21	1	550	231
Anchors	kg	1 237.8	Truck (2t)	1	900	1 800

strength portland cement with a nominal strength of 30 N/mm^2 and containing blast furnace slag cement with nominal strengths of 21 N/mm^2 and 18 N/mm^2 are used for other portions. Mix proportions and amounts of concrete used are shown in **Table 9**. Materials used in the manufacturing process are summarized in **Table 10**. The energy consumption and CO_2 emission caused by these materials are also shown in **Table 10**. For materials, 61 % of CO_2 emission is derived from concrete, while 39 % from steel. The amount of concrete used is greatly contributed to CO_2 emission amount.

Based on the information regarding suppliers of construction materials, distances from the suppliers to the construction site for transportation of materials are calculated and shown in **Table 11**. These suppliers are companies with whom the actual construction company of this bridge is connected regularly in business. For use of machines, the amounts are calculated from records and hearing and summarized in **Table 12**. From these results, environmental impact associated with transportation of materials and machines and use of machines is summarized in **Table 13**. Since rubber supports, rubber joints, unseating prevention devices, and anchors are planned to be supplied more than 500 km far from the construction site, environmental impact for transportation becomes large. PC wires and sheaths are also planed to be supplied more than 250 km far from the construction site.

Based on amounts shown in **Table 10** and **Table 13** which are considered as conventional materials and methods, alternative materials and methods are proposed. As for materials, high range water reducing admixture is used for concrete containing high strength portland cement instead of normal water reducing admixture to reduce the cement content of the concrete. Modified mix proportions and amounts of ready-mix concrete due to the use of high range water reducing admixture are shown in **Table 14**. As for construction, suppliers of PC wires, sheaths, rubber supports, rubber joints, unseating prevention devices, and anchors are changed to the nearest companies from the construction site. By this change, transportation distances of construction materi-

Table 12 Amounts of use of machines (PC bridge).

Machine	Amount
Truck crane (5t capacity)	79 hours
Truck crane (20t capacity)	192.5 hours
Truck crane (60t Capacity)	21 hours
Agitator truck (4.5m^3)	105 hours
Truck mounted concrete pump	89.8 m^3
Diesel generator (20kVA)	204 hours

Table 13 Environmental impact in construction stage (PC bridge).

	Energy consumption (GJ)	CO_2 emission (kg-CO_2)
Environmental impact caused by transportation of materials	55.26	3 509.9
Environmental impact caused by the use of construction machines	198.43	13 454.3
Total	253.69	16 964.2

Table 14 Mix proportions and total amounts of ready-mixed concrete using alternative material (PC bridge).

Type	Unit content (kg/m^3)						Amount (kg)					
	HC	BB	W	S	G	Ad.	HC	BB	W	S	G	Ad.
40-8-20 (H)	451	-----	160	673	1047	6.304	67 921	-----	24 096	101 354	157 678	949.4
30-8-20 (H)	364	-----	160	739	1054	4.585	15 470	-----	6 800	31 408	44 795	194.9
21-8-20 (BB)	-----	270	162	837	1017	1.465	-----	4 563	2 738	14 145	17 187	24.8
18-8-20 (BB)	-----	254	165	866	992	1.378	-----	7 010	4 554	23 902	27 379	38.0
Total	-----	-----	-----	-----	-----	-----	83 391	11 573	38 188	170 809	247 039	1 207.1

*) HC: High strength portland cement, BB: Blast furnace slag cement (Type B)

Table 15 Alternative suppliers of construction materials (PC bridge).

Material	Unit	Amount	Transportation method	Number of truck used	Distance from supplier to the site (km)	Total transportation distance (km.truck)
Ready-mixed concrete	m^3	240.4	Agitator truck (4.5m^3)	57	15	1 710
Frames	t	8.2	Truck (10t)	1	50	100
Steel bars (D16, D19, and D22)	kg	26 674.1	Truck (10t)	3	110	660
Steel bars (D10 and D13)	kg	7 821.0	Truck (10t)	1	80	160
PC wires	kg	7 754.9	Truck (10t)	1	110	220
Portal crane and erection girder			Truck (10t)	5	50	500
Sheaths	kg	613.6	Truck (4t) x 0.15	1	110	33
Rubber supports and rubber joints	kg	166.2	Truck (4t) x 0.04	1	110	8.8
Drain devices	kg	218.8	Truck (4t) x 0.05	1	90	9
Unseating prevention devices	kg	830	Truck (4t) x 0.21	1	110	46.2
Anchors	kg	1 237.8	Truck (2t)	1	110	220

Table 16 Reduction of environmental impact by alternative materials and methods (PC bridge).

	Energy consumption (GJ)	CO_2 emission (kg-CO_2)
(Manufacturing stage)		
Alternative materials	1 251.5	125 923
Standard materials	1 292.0	133 584
Reduction rate	-3.13%	-5.73%
(Construction stage)		
Alternative method	240.07	16 099.2
Standard method	253.69	16 964.2
Reduction rate	-5.37%	-5.10%

Table 17 Mix proportion of concrete used in each case (overflow dike).

	Slump (cm)	Air (%)	W/B 1)	s/a (%)	Unit content (kg/m^3)					
					W	C	Add. 2)	S	G	Ad.
Case-1	5	3	0.60	48	168	280	-----	897	979	1.68 3)
Case-2	8	3	0.47	45	168	358	-----	811	1 003	2.86 4)
Case-3	8	3	0.42	46	145	300	45	857	1 014	-----

1) Water binder ratio, 2) High strength additive, 3) Air entraining and water reducing admixture, 4) Superplasticizer

als are changed as shown in **Table 15**.

Reduction of environmental impact due to the adoption of alternative materials and methods is shown in **Table 16**. From this table, CO_2 emissions in the manufacturing stage and in the construction stage can be reduced 5.73 % and 5.10 %, respectively. These reductions satisfy the criteria required in **Table 8**. Consequently the verification of environmental performance requirement for this PC bridge is completed.

4.3 Overflow dike of dam

The overflow dike of a dam using high strength concrete was studied (JSCE 2004). Regarding the following three cases, the construction of an apron portion of 2000 m^2 which was prospected to be abraded by discharge water was studied.

Case-1: use of normal concrete (compressive strength: 35 N/mm^2)

Case-2: use of high strength concrete (compressive strength: 50 N/mm^2)

Case-3: use of high strength concrete containing high strength additive (compressive strength: 75 N/mm^2)

High strength additive used in Case-3 mainly consists of anhydrous gypsum and siliceous powder. This admixture contains powdered high range water reducing admixture (Yamamoto *et al.* 1999, 2002; Matsunaga *et al.* 2001).

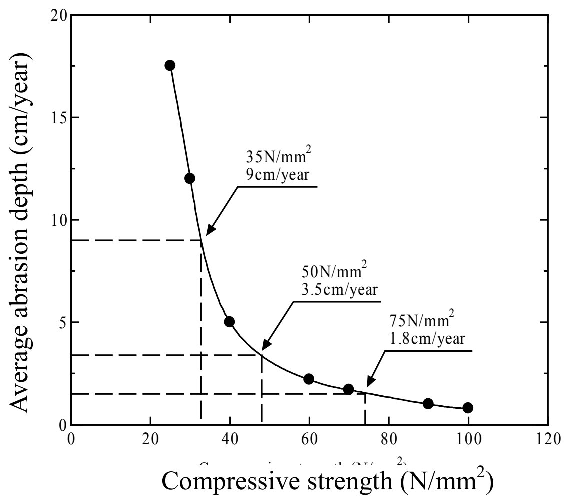


Fig. 3 Relationship between compressive strength of concrete and average abrasion depth of concrete due to discharge (arranged based on Matsunaga *et al.* 2001).

Mix proportion of concrete in each case is shown in **Table 17**.

It is assumed that the service life span of this dam is 100 years and that a repairing work is done when 0.45 m of the apron portion in thickness is abraded. In the repair, 50 mm of the surface in thickness is removed and the concrete waste is transported to a landfill site and disposed. For concrete volume, 2000 m^3 of concrete is used for new construction and 1000 m^3 for every repairing work.

From the relationship between compressive strength of concrete and average abrasion depth of concrete due to discharge shown in **Fig. 3**, 19 times, 8 times, and 3 times of repairing works are needed for 100 years in Case-1, Case-2, and Case-3, respectively. Therefore, 20000 m^3, 9000 m^3, and 4000 m^3 of total concrete are used for 100 years in Case-1, Case-2, and Case-3, respectively. Hereby 2000 m^3, 900 m^3, and 400 m^3 of waste concrete are generated for 100 years in Case-1, Case-2, and Case-3, respectively because approximately 100 m^3 (2000 m^2 x 50 mm) of waste concrete is emitted in one repairing work.

The estimation of environmental performance was carried out regarding materials used and construction processes in the new construction and the repairing works. The estimation results are summarized in **Table 18** and **Table 19**. The difference of the frequency of the repair due to abrasion in each case affects the results.

The values shown in **Table 19** are results calculated by Life Cycle Impact Assessment Method based on Endpoint Modeling (LIME). The LIME is one of integration methods of environmental impact and has been developed in Japan (JEMAI 2004). The LIME method sets forth four objects of protection consisting of human health, public assets, biodiversity, and primary production capacity, which have unique indexes consisting of DALY (Disability-Adjusted Life Year, unit: year), YEN (Japanese monetary unit, unit: yen), EINES (Expected Increase Numbers of Extinct Species, unit: species) and NPP (Net Primary Productivity, unit: t/ha/year), respectively. The degree of environmental impact can be evaluated with these four indexes and furthermore with a single index that is an integrated index of these four indexes. The single index has three versions. The weighting factors for single indexes ver. 1 and ver. 2 have been obtained from the conjoint analysis that has been developed primarily in marketing research as a tool for measuring consumer preference. Single index ver. 1 uses the yen unit and its weighting factor is an amount of marginal willingness to pay (MWTP) for each damage item, while single index ver. 2 has no dimension and its weighting factor is a ratio of each annual damage amount calculated from the product of the amount of MWTP for each damage item and its annual magnitude. The weighting factors for single index ver. 3 are obtained from the AHP (Analytic Hierarchy Process) method that is a multi-criteria decision-making approach and indicates decisions by weighing the evaluation criteria and making pair-wise judgments of a set of alternatives. Single index ver. 3 has no dimension. Since the significance of the utilization of this index is to enable comparison between the degrees of environmental impact for each case, either version of the index can be used and it is thought that the magnitude of the index itself is not too important here. But there is a possibility that a value obtained from single index ver. 1 having a monetary unit is considered as expense for environment and applied to calculation of the sum of construction cost and environmental cost.

From the results shown in **Table 18**, it is found that the environmental impact caused by concrete structure construction can be evaluated with each environmental performance factor such as material recycling, gas emissions, particulate matter emission, and waste emission if the inventory data regarding these factors are totally prepared. Inventory data regarding environmental impact published or prepared in each institute will be different since basic data for calculation are different. For instance, inventory data calculated from the process analysis method and from the input-output analysis method should be different. It does not mean that inventory data themselves are meaningless but it is important to evaluate environmental performance using a set of inventory data prepared under a specified condition,

Table 18 Emission amount of each case (overflow dike).

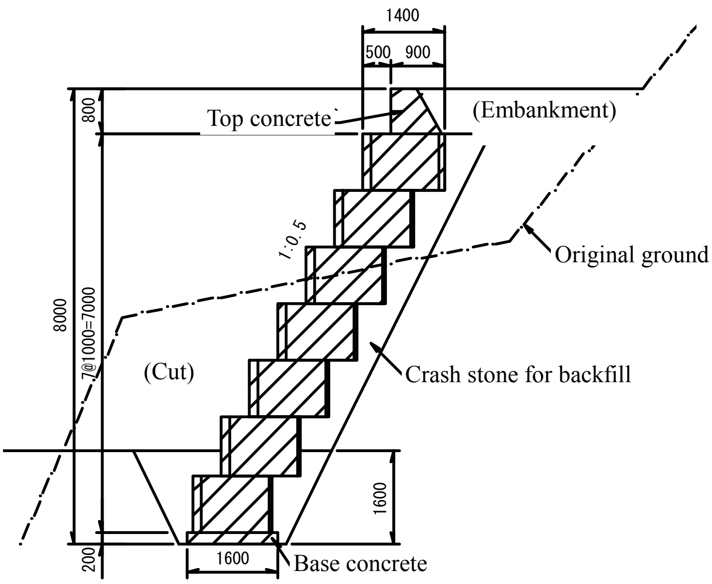
	Material recycling (wet-kg)	Waste emission (wet-kg)	CO_2 emission (kg)	SO_x emission (kg)	NO_x emission (kg)	Particulate matter emission (kg)
Case-1	$8.27x10^5$	$3.23x10^6$	$8.72x10^6$	$2.02x10^3$	$1.67x10^4$	$7.26x10^2$
Case-2	$4.76x10^5$	$1.45x10^6$	$4.47x10^6$	$9.97x10^2$	$8.62x10^3$	$3.51x10^2$
Case-3	$1.77x10^5$	$6.45x10^5$	$1.82x10^6$	$4.21x10^2$	$3.49x10^3$	$1.50x10^2$

Table 19 Damage amounts and integration results of each case (overflow dike).

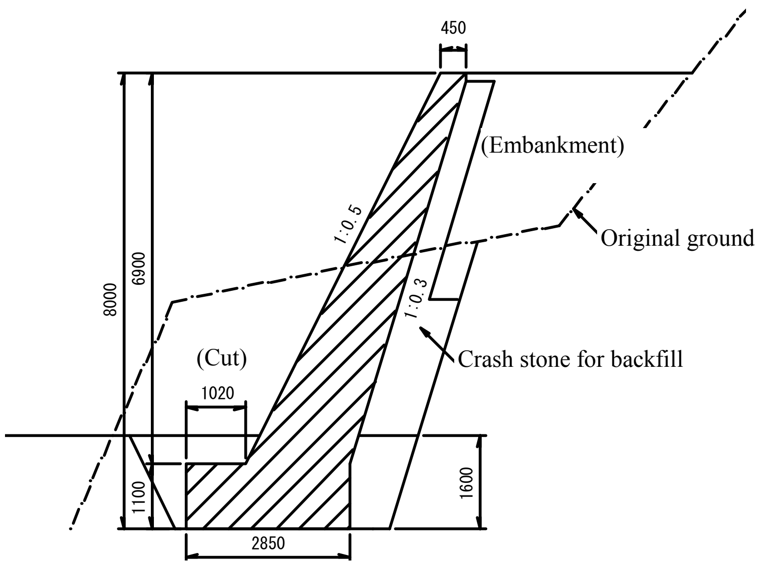
	Damage amounts				Integration results		
	Human health [DALY] (year)	Public assets [YEN] (yen)	Biodiversity [EINES] (species)	Primary production capacity [NPP] (t/ha/year)	Ver.1 (yen)	Ver.2 (No dim.)	Ver.3 (No dim.)
Case-1	1.27	$1.13x10^7$	$3.32x10^{-7}$	$3.51x10^2$	$3.23x10^7$	$1.87x10^7$	$1.87x10^7$
Case-2	0.64	$5.68x10^6$	$1.44x10^{-7}$	$1.64x10^2$	$1.59x10^7$	$9.24x10^6$	$9.23x10^6$
Case-3	0.26	$2.35x10^6$	$6.59x10^{-8}$	7.11x10	$6.67x10^6$	$3.87x10^6$	$3.87x10^6$

not to mix up and use some sets of inventory data prepared by some different institutes. From the results shown in **Table 19**, moreover, it is found that the integrated evaluation using several environmental performance factors can be also carried out.

For all environmental performance factors in **Table 18** and all damage amounts and integration results in **Table 19**, the results of Case-3 give the lowest values. Consequently Case-3 will be selected in this case study.



Case-1: Retaining wall using hollow blocks



Case-2: Retaining wall constructed in situ

Fig. 4 Schematic view of retaining walls studied.

Table 20 Mix proportion of concrete (retaining wall).

	W/C	Unit content (kg/m^3)				
		W	C	S	G	Ad.
Hollow block	0.49	165	337	742	1 124	2.36
Ready-mixed concrete	0.61	156	256	822	1 117	0.640

C: Blast furnace slag cement (Type B), Ad.: High range water reducing admixture

4.4 Retaining wall

Regarding the following two cases, the construction of a retaining wall (height: 8.0 m, slope: 1:0.5, length: 120 m) was studied (JSCE 2004).

Case-1: a retaining wall using hollow blocks

Case-2: a retaining wall constructed in situ

For the retaining wall of Case-1, hollow blocks are piled up before connecting them with ready-mix concrete and steel bars. Soils emitted during the construction are treated in the site by being filled in the hollow blocks. Together with transportation of concrete products resulting in little concrete placing in situ, reduction of construction term and secure concrete quality can be expected. The schematic view of the retaining walls is shown in **Fig. 4**.

In this case study, manufacturing of materials, transportation of construction materials, construction, and treatment of wastes are estimated. Mix proportions of concrete used here are shown in **Table 20**. Ready-mixed concrete used in Case-1 and Case-2 is the same. Total

Table 21 Total amounts used for calculation in each case (retaining wall).

				Unit	Case-1	Case-2
Manufacture of materials	Hollow block	Material	Blast furnace slag cement (Type B)	t	109.9	-----
			Fine aggregate	t	241.9	-----
			Coarse aggregate	t	366.4	-----
			Steel	t	13.4	-----
		Production	Process in plant	t	772.8	-----
			Form vibrator	h	93.3	-----
			Steam curing	m^3	326.0	-----
	Ready-mixed concrete	Material	Blast furnace slag cement (Type B)	t	67.6	337.9
			Fine aggregate	t	217.0	1 085.0
			Coarse aggregate	t	294.9	1 474.4
		Production	Process in plant	t	620.9	3 103.2
	Steel bar			t	3.3	-----
	Crash stone for backfill			t	910.0	1 111.0
Transportation of materials	Ready-mixed concrete	Agitator truck (4.5m^3)		km.m^3	10 560.0	52 800.0
	Crash stone for backfill	Truck (10t)		km.t	91 000.0	111 100.0
	Hollow block	Truck (10t)		km.t	75 300.0	-----
	Steel bar	Truck (10t)		km.t	330.0	-----
	Wood form	Truck (10t)		km.t	170.0	1 230.0
Construction	Soil excavation	Excavator (0.6m^3)		h	46.2	49.2
	Excavation for foundation	Excavator (0.6m^3)		h	14.4	24.6
	Placing of hollow block	Truck crane (15-16t)		h	90.0	-----
	Backfill of foundation	Excavator (0.6m^3)		h	9.6	16.8
		Tamper (60-100kg)		h	43.2	75.6
	Crash stone for backfill	Excavator (0.6m^3)		h	70.2	85.8
	Embankment	Excavator (0.6m^3)		h	27.9	39.0
		Tamper (60-100kg)		h	125.4	175.2
	Compaction in hollow block	Excavator (0.6m^3)		h	27.6	-----
		Tamper (60-100kg)		h	124.2	-----
	Scaffold work	Wheel crane (25t)		h	-----	63.6
	Placing of ready-mixed concrete	Agitator truck (4.5m^3)		h	60.0	294.0
		Truck crane (15-16t)		h	36.0	60.0
Waste treatment	Surplus soil			t	646.0	1 731.0

Table 22 Emission amount of each case (retaining wall).

	Material recycling (wet-kg)	Waste emission (wet-kg)	CO_2 emission (kg)	SO_x emission (kg)	NO_x emission (kg)	Particulate matter emission (kg)
Case-1	1.51×10^4	6.46×10^5	1.71×10^5	7.3×10	6.71×10^2	5.0×10
Case-2	2.88×10^4	1.73×10^6	2.56×10^5	1.05×10^2	1.18×10^3	6.3×10

Table 23 Damage amounts and integration results of each case (retaining wall).

	Damage amounts				Integration results		
	Human health [DALY] (year)	Public assets [YEN] (yen)	Biodiversity [EINES] (species)	Primary production capacity [NPP] (t/ha/year)	Ver.1 (Yen)	Ver.2 (No dim.)	Ver.3 (No dim.)
Case-1	0.0568	2.82×10^5	5.02×10^{-8}	2.21×10	1.52×10^6	8.83×10^5	9.24×10^5
Case-2	0.0812	4.16×10^5	1.32×10^{-7}	4.95×10	2.84×10^6	1.65×10^6	1.70×10^6

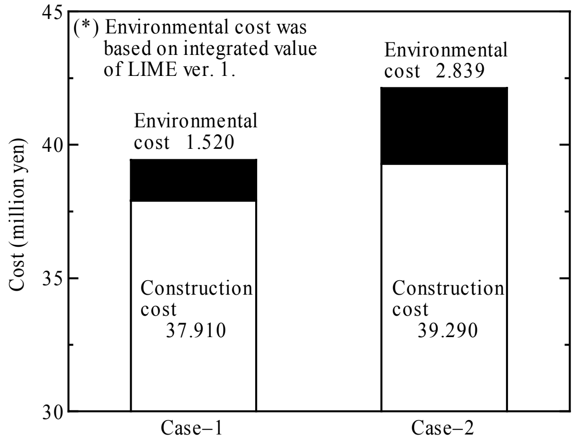


Fig. 5 Comparison between construction cost and environmental cost in each case (retaining wall).

amounts used for calculation in each case are listed in **Table 21**.

Estimation results are shown in **Table 22**. Since the use of hollow blocks leads to reduction of concrete volume, every emission amount becomes very low in Case-1 compared with Case-2. Regarding damage amounts shown in **Table 23**, the reduction of damages for biodiversity and primary production capacity is much larger than that of damages for human health and public assets. This is because waste emission is significantly reduced in Case-1 by effective use of surplus soils in hollow blocks.

In this case study, cost analysis was also carried out. Using the values of single index ver. 1 of integration results shown in **Table 23** which have a monetary unit, the sum of construction cost and environmental cost is compared in both cases. The results are shown in **Fig. 5**. When environmental cost is added to construction cost, the difference between the total costs for Case-1 and Case-2 becomes large. Although there is a problem how environmental cost can be considered in actual construction, that is to say, who pays for environmental cost, it is found that the concept of cost considering environmental impact can be introduced in a bidding system.

From these results, Case-1 should be selected in this case study.

4.5 Secondary lining in tunnel

A secondary lining using concrete with recycled aggregate in a tunnel was studied (JSCE 2004). A schematic view of the tunnel is shown in **Fig. 6**. The lengths of the tunnel are assumed to be 500 m, 1000 m, and 2000 m. The following three kinds of combinations of fine and

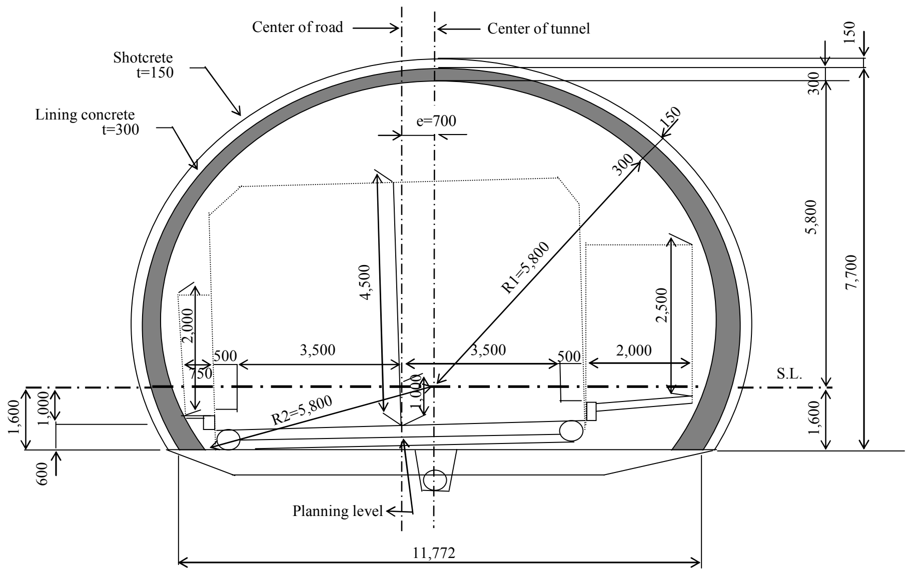


Fig. 6 Schematic view of a tunnel studied.

Table 24 Mix proportion of concrete in each case (secondary lining).

	Slump (cm)	Air (%)	W/C	s/a (%)	Unit content (kg/m^3)				
					W	C	S	G	Ad.
Case-1	12	4.5	0.609	48.6	170	279	881	967	6.8
Case-2	12	4.5	0.609	48.6	160	263	900	988*	6.6
Case-3	12	4.5	0.609	48.6	160	263	900**	988**	6.6

Ad.: Air entraining and water reducing admixture
*: Recycle aggregate ground mechanically
**: Recycled aggregate treated with a heating and rubbing method

Table 25 Total amounts used for calculation for 1000 m lining in each case (secondary lining).

				Unit	Case-1	Case-2 & -3
Manufacture of materials	Ready-mixed concrete	Material	Ordinary portland cement	t	1 800	1 696
			Fine aggregate	t	5 682	6 451
			Coarse aggregate	t	6 237	6 373
		Production	Process in plant	m^3	6 450	6 450
	Reinforcing steel bar			t	130	130
Transportation	Ready-mixed concrete	Agitator truck (4.5m^3)		km.m^3	129 000	129 000
Construction	Sliding form			h	230	230
	Truck mounted concrete pump (40m^3/h)			m^3	6 450	6 450
	Vibrator (0.2kW x 4, operated for 7.2h/day)			h	691	691

Table 26 Emission amount of each case (secondary lining).

Length of tunnel		Material recycling (wet-kg)	Waste emission (wet-kg)	CO_2 emission (kg)	SO_x emission (kg)	NO_x emission (kg)	Particulate matter emission (kg)
500 m	Case-1	$1.33x10^5$	$4.26x10^2$	$7.91x10^5$	$5.49x10^2$	$1.58x10^3$	4.46x10
	Case-2	$3.31x10^6$	$4.26x10^2$	$7.84x10^5$	$5.66x10^2$	$1.61x10^3$	4.52x10
	Case-3	$6.21x10^6$	$4.26x10^2$	$1.42x10^6$	$7.45x10^2$	$2.02x10^3$	$5.93x10^2$
1000 m	Case-1	$2.66x10^5$	$8.53x10^2$	$1.58x10^6$	$1.10x10^3$	$3.16x10^3$	8.92x10
	Case-2	$6.62x10^6$	$8.53x10^2$	$1.57x10^6$	$1.14x10^3$	$3.23x10^3$	9.18x10
	Case-3	$1.22x10^7$	$8.53x10^2$	$2.89x10^6$	$1.49x10^3$	$4.18x10^3$	$1.17x10^3$
2000 m	Case-1	$5.31x10^5$	$1.71x10^3$	$3.16x10^6$	$2.20x10^3$	$6.31x10^3$	$1.78x10^2$
	Case-2	$1.32x10^7$	$1.71x10^3$	$3.14x10^6$	$2.27x10^3$	$6.44x10^3$	$1.81x10^2$
	Case-3	$2.49x10^7$	$1.71x10^3$	$5.68x10^6$	$2.98x10^3$	$8.08x10^3$	$2.37x10^3$

Table 27 Damage amounts and integration results of each case (secondary lining).

		Damage amounts				Integration results		
Length of tunnel		Human health [DALY] (year)	Public assets [YEN] (yen)	Biodiversity [EINES] (species)	Primary production capacity [NPP] (t/ha/year)	Ver.1 (Yen)	Ver.2 (No dim.)	Ver.3 (No dim.)
500 m	Case-1	0.244	$9.79x10^5$	$1.63x10^{-8}$	4.58x10	$4.35x10^6$	$2.52x10^6$	$2.78x10^6$
	Case-2	0.246	$9.72x10^5$	$1.14x10^{-8}$	3.39x10	$4.10x10^6$	$2.38x10^6$	$2.63x10^6$
	Case-3	0.455	$2.10x10^6$	$5.36x10^{-8}$	1.77x10	$6.90x10^6$	$4.01x10^6$	$4.35x10^6$
1000 m	Case-1	0.488	$1.96x10^6$	$3.28x10^{-8}$	9.17x10	$8.70x10^6$	$5.05x10^6$	$5.56x10^6$
	Case-2	0.494	$1.95x10^6$	$2.40x10^{-8}$	7.08x10	$8.28x10^6$	$4.81x10^6$	$5.31x10^6$
	Case-3	0.912	$4.25x10^6$	$1.12x10^{-8}$	3.69x10	$1.39x10^7$	$8.06x10^6$	$8.75x10^6$
2000 m	Case-1	0.977	$3.91x10^6$	$6.53x10^{-8}$	$1.83x10^2$	$1.74x10^7$	$1.01x10^7$	$1.11x10^7$
	Case-2	0.985	$3.89x10^6$	$4.56x10^{-8}$	$1.35x10^2$	$1.64x10^7$	$9.52x10^6$	$1.05x10^7$
	Case-3	1.81	$8.42x10^6$	$2.15x10^{-8}$	7.08x10	$2.76x10^7$	$1.60x10^7$	$1.74x10^7$

coarse aggregates for tunnel lining concrete were investigated.

Case-1:natural fine and coarse aggregates

Case-2:natural fine aggregate and recycled coarse aggregate ground mechanically

Case-3:recycled fine and coarse aggregates treated with a heating and rubbing method

A heating and rubbing method is a unique method developed in Japan in order to obtain high quality recycled aggregate (Shima et al. 2005). It is assumed that ready-mixed concrete was made in a plant and transferred to the construction site. Mix proportion of concrete in each case is shown in **Table 24**. The cross-sectional area of secondary lining is 6.45 m2. The volume of concrete used for the lining of the tunnel of 500 m, 1000 m, and 2000m are 3225 m^3, 6450 m^3, and 12900 m^3, respectively. A sliding form of 10.5 m in

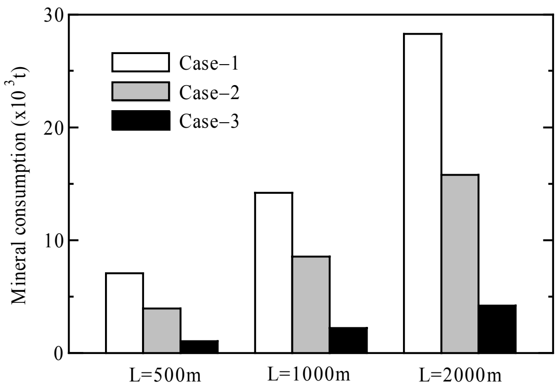


Fig. 7 Comparison of mineral consumption for each case (secondary lining).

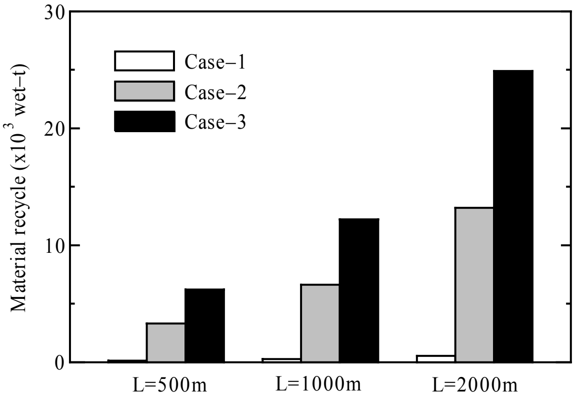


Fig. 8 Comparison of material recycle for each case (secondary lining).

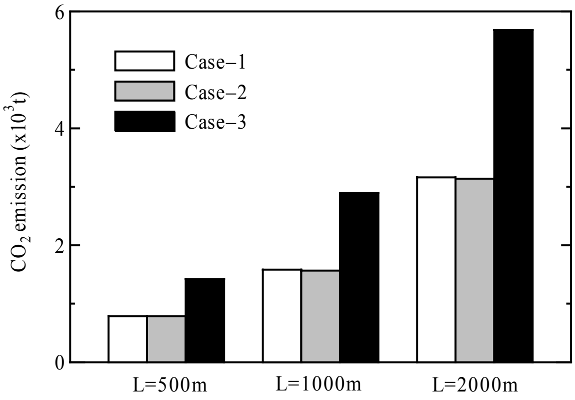


Fig. 9 Comparison of CO_2 emission for each case (secondary lining).

length is used and its electric power in use and its operation time are assumed to be 22 kW and 2.4 hours per day, respectively. Total amounts used for calculation for 1000 m lining are shown in **Table 25** as an example. For 500 m and 2000 m linings, total amounts of each in **Table 25** become half and twice, respectively.

Estimation results are shown in **Table 26** and **Table 27**. Based on the results in **Table 26**, mineral consumption, material recycle, and CO_2 emission for each case are compared in **Fig. 7**, **Fig. 8**, and **Fig. 9**, respectively. Since recycled coarse aggregate in Case-2 and recycled fine and coarse aggregates in Case-3 are used, mineral consumptions are smaller and material recycles are larger in Case-2 and Case-3 than those in Case-1. But as shown in **Fig. 9**, since large energy is needed in recycling processes in Case-3, CO_2 emission in Case-3 becomes much larger than those in Case-1 and Case-2. Since CO_2 emissions of natural crashed coarse aggregate and recycled coarse aggregate ground mechanically are almost same, CO_2 emissions in Case-1 and Case-2 are almost same. From these results, Case-2 should be best among these three cases, which can be said from the integration results in **Table 27**. From damage amounts in **Table 27**, it is found that the influence on the object of protection is different in an environmental impact factor. In Case-3 where CO_2 emission is large, the damage amounts for human health and biodiversity are very large compared with Case-1 and Case-2, while the damage amount for primary production capacity is small. Regarding the damage for biodiversity, the amount in Case-3 is larger in 500 m lining than those in Case-1 and Case-2, but smaller in 1000 m and 2000 m linings. Therefore, the difference of the object of protection focused on could change the choices in the verification or selection. This can be said also when the integration method is adopted. As shown in **Table 27**, the relation among the magnitudes in Case-1, Case-2, and Case-3 is different in length of lining and in integration version.

5. Discussions

5.1 Inventory data

In this study, emission inventory data associated with the life of a concrete structure were totally prepared by the process analysis based on intensive literature survey and hearing to the institute concerned. By using these data, environmental performance within the life cycle of a concrete structure can be evaluated. As a matter of course, these do not include emission inventory data regarding all materials or all works concerning material manufacturing, transportation, construction, maintenance, demolition, and disposal and recycling of concrete structures. But emission inventory data of which materials and works are not included here could be estimated by expanding the inventory data of appropriate material or work shown here. Since concrete of civil infrastructures is primarily focused on in this study, emission inventory data for interior materials, insulators, and so on that are mainly used in buildings are not investigated.

The process analysis was used to collect data in this study. It is obvious from a theoretical point of view that the values for inventory are changed if the input-output analysis is used. This is because of different approach to be employed in the calculation of inventory data between two analytical methods. The input-output analysis includes a ripple effect and the direct influence of price within the analytical domain of corresponding data (JSCE1997). On the other hand, in the process analysis the inventory data of a product are determined by the relationship of the total amount of its shipment with the total energy consumed in the corresponding factory to manufacture it. Accordingly the amount of emission gas can be calculated on a single product base. This approach enables detailed analysis and reliable data to be obtained while much efforts and continuous hearing to a manufacture are inevitable to up-date the corresponding data (JSCE 1997).

Also the values should be varied by region of the world due to different methodology and technology to be employed. As an example cement CO_2 emissions are

Table 28 Comparison of unit-based CO_2 emissions in cement manufacturing by region and sub-region for the year 2000.

Region unit-based emissions		Sub-region unit-based emissions	
Region name	kg CO_2 per kg cement	Sub-region name	kg CO_2 per kg cement
North America	0.99	USA	0.99
		Canada	0.91
Western Europe	0.84	Western Europe	0.84
Asia	0.89	Japan	0.73
		Australia & New Zealand	0.79
		China	0.90
		South East Asia	0.92
		Republic of Korea	0.90
		India	0.93
Eastern Europe	0.83	Former Soviet Union	0.81
		Other Eastern Europe	0.89
South & Latin America	0.82	South & Latin America	0.82
Middle East & Africa	0.85	Africa	0.85
		Middle East	0.85
Global Average	0.87		0.87

shown in **Table 28** (Battelle 2002). Therefore worldwide standardization of inventory data may be difficult, although preparation of emission inventory data itself in each region is of course extremely important because of understanding the state of emissions in each region. Relative comparison of the magnitudes of inventory in each region should be possible. That is to say, preparation of emission inventory data makes it possible to clarify what measures should be taken to effectively reduce environmental burden associated with the life of concrete structures.

The significance of this study is the preparation and supply of common emission inventory data that can be referred to by researchers to discuss a possibility to reduce environmental impact totally and effectively for the life of concrete structures and to develop technologies to reduce the environmental impact. It is generally understood that efforts to reduce environmental impact consume energy resulting in the increase of environmental impact on the contrary. For instance, the higher the quality of recycled aggregate is required, the more the energy will be needed as shown in the case study on the secondary lining of a tunnel. But when concrete structure construction is considered totally and systematically, there could be a technology by which environmental impact is reduced. This technology may be led with changes of a structural shape and a construction method. The preparation of emission inventory data will make it possible to discuss such development of technologies. Including this sense, it is supposed that the collection of inventory data in this study sufficiently accomplishes the above purposes.

Many LCA tools have been already developed and widely used all over the world. Some of them are focused on the environmental evaluation of the construction based on the materials and structural elements used (for example, BEES, Envest, and Eco-Quantum), some on the evaluation of different industrial processes (for example, GEMIS and SimaPro), and some are focused on more general aspects of the sustainability of structural components and buildings (for example, GBTool, BREEAM, and LEAD) (Lippiatt 2002; Goedkoop and Oele 2004; Cole and Larsson 2002; *fib* 2004). The main differences among them are in the specification of goal and scope of the evaluation process and in the definition and recognition level of the corresponding solution system. The differences between this study and those tools are database and evaluation methodologies. The database of this study is prepared based on the Japanese market. Therefore this database is a regional one but directly reflects Japan's industrial states. Regarding the methodologies, original methods for evaluating environmental impact have been developed by the authors (Kawai *et al.* 2005). These methods can be directly used in the verification process of designs of concrete structure construction.

In future works, it will be needed to prepare more substantial inventory data. Sensitive analysis of each inventory may be also needed to clarify which factor is significantly affected by change in the value of inventory by year and by region.

5.2 Case studies

Four case studies were carried out in order to confirm the applicability of the inventory data prepared in this paper to environmental performance evaluation of concrete structures. As methods for evaluating environmental performance of concrete structures, design methods considering environmental impact that were previously proposed by the authors were used.

In the first case study, in order to confirm the effectiveness of design method verifying environmental performance that is one of design methods proposed in the previous paper (Kawai *et al.* 2005), environmental performance was set up as criteria before verifying its performance by comparing conventional and alternative materials and construction methods. As a result, the achievement of the criteria by adopting alternative materials and construction methods was verified. Through this case study, it was clarified that environmental impact of a concrete structure can be evaluated as a performance parameter of the structure similar to serviceability, safety, and durability performance. In an actual case, however, the verification of environmental performance is not carried out separately, but four performance parameters of serviceability, safety, durability, and environmental impact are totally and harmoniously verified. In that case, either performance parameter could be given priority to. When this verification is performed, who sets up conventional or standard materials and construction methods could be a problem. In many cases, an owner of the structure should prepare for standard materials and construction methods.

Other three case studies were carried out to confirm the effectiveness of design method considering environmental performance that is another design method proposed in the previous paper (Kawai *et al.* 2005). Although in design method considering environmental performance two methods of verification and selection are prepared to evaluate environmental performance of a concrete structure (Kawai *et al.* 2005), in these case studies which method of verification or selection is adopted is not specified. In this sense, every case study can be said to be a case study for selection. If some criterion regarding environmental impact is set up, the comparison of each case in every case study will become a process of verification. Otherwise, this comparison is a process of selection in which environmental performance is totally evaluated. It can be said that these case studies of the overflow dike of a dam, the retaining wall, and the secondary lining in a tunnel are especially focused on environmental performance of binding material, construction waste, and material recycling, respectively, in addition to different structure type. Although in these cases, as mentioned above, specific environmental performance requirements were not prepared for, it is obvious that different material or construction method is comparable even when environmental performance requirement is qualitative.

Importance of environment-conscious design is well understood all over the world. The OECD (2003) published the guidance for the design of government policies to address the environmental impacts of the building sector. They mentioned especially about the reductions of CO_2 emissions, minimization of construction and demolition waste, and prevention of indoor air pollution, but the contents did not include concrete design methods but just policy instruments. The ISO (2002) is also preparing for guidelines for considering environmental impacts regarding buildings and construction assets. They provide a framework of environment-conscious design, but it does not include concrete method, either. Ministry of Land, Infrastructure and Transport, Japan is pressing forward with the coordination of Green Government Building which will become the models responding to the environmental preservation measures in Japan's architectural field (MLIT 1998). They show guidelines for greenification which consist of targets for efforts. Quantitative evaluation of efforts is not referred to. The case studies shown here could prove that design method verifying environmental performance and design method considering environmental performance can be used as a concrete method for achieving the above-mentioned motions.

6. Conclusions

The preparation of the inventory data for evaluating environmental impact of concrete structure construction through deliberately conducted literature survey and hearing to the institutes concerned and four case studies using these inventory data to confirm the effectiveness of concrete structure design methods considering environmental impact were performed in this paper. As a result, the following conclusions can be drawn.

(1) Common basis for the estimation of emission inventory data was proposed for evaluating environmental impact of a concrete structure through its life cycle. Since various kinds of raw materials and processing are employed and construction machinery are diverse for constructing a concrete structure and its demolishment and disposal and recycling, inventory data regarding 91 detail items in total were able to be provided in this paper.

(2) Emission inventory data of concrete materials, other materials involved, construction works, demolition works, and disposal and recycling were provided for CO_2, SO_x, NO_x, and particulate matter.

(3) Fundamental inventory data of various kinds of energy such as electric power, LPG for fuel, LNG (imported), light oil, gasoline, heavy oil, kerosene, and acetylene gas were clarified. In addition, the method to estimate inventory data regarding the use of construction machinery, instruments, and other equipment that are normally employed in concrete structure construction, demolition works, and disposal and recycling was given.

(4) Significance of compiling inventory data was discussed with regard to quantitatively evaluating environmental impact of a concrete structure.

(5) Design method verifying environmental performance which was proposed by the authors is applicable to

evaluate environmental impact as a performance parameter of a concrete structure when a quantitative requirement for environmental impact is prepared.

(6) Design method considering environmental performance which was proposed by the authors is also applicable to evaluate environmental impact as a performance parameter of a concrete structure regardless of preparation of a quantitative requirement for environmental impact.

(7) Environmental impact of a concrete structure can be evaluated in terms of not only environmental impact factors such as CO_2 emission, NO_x emission, SO_x emission, and waste emission but also the objects of protection such as human health, public assets, biodiversity, and primary production capacity, and moreover in terms of the integrated index of the objects of protection.

(8) By using an integrated index, monetary evaluation considering both construction cost and environmental impact can be performed.

(9) Relative magnitudes among the damage amounts of the objects of protection are different in environmental impact factor. Therefore the difference in the amount of each environmental impact factor could change the results of relationship among the damage amounts of the objects of protection.

Acknowledgements

This study was carried out by the Sub-Committee on Assessment for Environmental Impact of Concrete, Committee on Concrete, Japan Society of Civil Engineers, Japan. The authors would like to express our gratitude to all members of this sub-committee for their devoted contributions. A part of this study was supported by Grant-in-Aid for Scientific Research No.14350234 from Japan Society for the Promotion of Science (JSPS), Japan, by Grant-in-Aid for Scientific Research from the Kajima Foundation, Japan, and by Grant-in-Aid for Special Research from Electric Technology Research Foundation of Chugoku, Japan.

References

ANRE (2004). "*Regarding the revision of the standard calorific value table by energy resource*." Agency for Natural Resources and Energy. (in Japanese)

Battelle (2002). "*Toward a sustainable cement industry – Substudy 8: Climate change*." Conches-Geneva: World Business Council for Sustainable Development.

Cole, R. and Larsson, N. (2002). "*Green building challenge 2002 – GBTool user manual*." Ottawa: International Initiative for a Sustainable Built Environment.

CRI (1998). "*Data book on the calculation of renting construction machinery*." Construction Research Institute. (in Japanese)

CRR (1997). "*Guidebook on the use of concrete by-products for civil projects*." Collaboration Research Report on Intense Treatment and Utilization Technology of Concrete By-Products. (in Japanese)

FEPC (2004a). "*Environmental action plan by the Japanese electric utility industry*." The Federation of Electric Power Companies of Japan.

FEPC (2004b). "*Electricity review Japan [2003-2004]*." The Federation of Electric Power Companies of Japan.

fib (2004). "Environmental design." Lausanne: the International Federation for Structural Concrete (*fib*), *fib* Bulletin 28, 63-74.

Goedkoop, M. and Oele, M. (2004). "*SimaPro 6 – Introduction to LCA with SimaPro*." Amersfoort: PRé Consultants.

HOK (1988). "*Study on development of evaluation system for supporting integrated management of municipal waste*." Lab. of Solid Waste Disposal Engineering, Hokkaido University. (in Japanese)

Ishikawa, M. *et al*. Eds. (1999). "*LCA practice – Correspondence to ISO 14040*." Tokyo: Science Forum. (in Japanese)

ISO 14040 (1997). "*Environmental management – Life cycle assessment – Principles and framework*." Geneve: International Organization for Standardization.

ISO/DIS 15686-6 (2002). "*Buildings and construction assets – service life planning – Part 6: Guidelines for considering environmental impacts*." Geneve: International Organization for Standardization.

Jahren, P. (2004). "Greener concrete-The CO_2 case – What are the opinions?" *In: Eighth CANMET/ACI International Conference on Flyash, Silica Fume, Slag And Natural Pozzolans in Concrete*, Las Vegas *23-29 May 2004*. Supplementary Papers 299-315.

JCMA (1975). "*Collection and production of aggregate*." Japan Construction Mechanization Association. (in Japanese)

JCMA (2001). "*Equipment cost calculation chart, 2001*." Japan Construction Mechanization Association. (in Japanese)

JEMAI (2004). "*Report on development of assessment technology of life cycle environmental impacts of products and so forth*." Tokyo: Japan Environmental Management Association for Industry. (in Japanese)

JSCE (1997). "*Report on the environmental management and assessment of environmental impact in civil works*." Tokyo: Japan Society of Civil Engineers, Research Committee on Global Environment. (in Japanese)

JSCE (2002). "*Assessment for environmental impact of concrete*." Tokyo: Japan Society of Civil Engineers, Concrete Engineering Series 44. (in Japanese)

JSCE (2004). "*Assessment for environmental impact of concrete (Part 2)*." Tokyo: Japan Society of Civil Engineers, Concrete Engineering Series 62. (in Japanese)

Kawai, K. (2002). "A proposal of concrete structure design concept considering environmental performance." *In: International Conference on Civil and Environmental Engineering*, Higashi-Hiroshima

30-31 October 2002. 59-68.

Kawai, K. and Sugiyama, T. (2003). "Life cycle design concept considering environmental performance." *In: 2nd International Symposium on Integrated Lifetime Engineering of Building and Civil Infrastructures*, Kuopio *1-3 December 2003*. 73-78.

Kawai, K., Sugiyama, T., Kobayashi, K. and Sano, S. (2005). "A proposal of concrete structure design methods considering environmental performance." *Journal of Advanced Concrete Technology*, 3 (1), 41-51.

Lippiatt, B. C. (2002). "*BEES 3.0 - Building for environmental and economic sustainability, technical manual and user guide*." Gaithersburg: National Institute of Standards and Technology.

Malhotra, V. M. (2000). "Role of supplementary cementing materials in reducing greenhouse gas emissions." *In:* O. E. Gjørv and K. sakai Eds. *Concrete Technology for a Sustainable Development in the 21st Century*. London: E & FN Spon, 226-235.

Matsunaga, Y., Yamamoto, K., Morioka, M., Watanabe, Y., Sakai, E. and Daimon, M. (2001). "Effects of concrete added with high strength additive on reduction of environmental burden." *Journal of the Society of Materials Science, Japan*, 50 (4), 440-446. (in Japanese)

Matsuno, Y., Inaba, A. and Betz, M. (1998). "Evaluation of electricity grid mixes in Japan with application of life-cycle impact-assessment methodology." *In: Third International Conference on EcoBalance*, Tsukuba *25-27 November 1998*. 551-554.

Mitsubishi Materials (2001). "*Demolished concrete treatment service: Type III environmental label*." Products Environmental Aspect Declaration. (in Japanese)

MLIT (1998). "*Guidelines for the planning of environment-friendly government building*." Tokyo: Ministry of Land, Infrastructure and Transport, Japan.

MOE (2000). "*Report of the study group on the calculation methodology of the emissions of green house gases*." Ministry of the Environment. (in Japanese)

MOE (2003). "*White paper on the environment*." Tokyo: Ministry of the Environment. (in Japanese)

Nanzai, K, Moriguchi, Y. and Tohno, S. (2002) "*Embodied energy and emission intensity data for Japan using input-output Tables (3EID) – Inventory data for LCA –*." Center for Global Environmental Research, Independent Administrative Institution, National Institute for Environmental Studies. (in Japanese)

OECD (2003). "*Environmentally sustainable buildings – Challenges and policies*." Paris: Organization for Economic Co-operation and Development.

PEC (2002). "*Report on preparation of LCI by source of petroleum products and survey about environmental impact assessment of petroleum products*." Petroleum Energy Center. (in Japanese)

Péra, J. and Ambroise, J. (2000). "Incineration of wastes and the environment." *In:* R. K. Dhir, T. D. Dyer and K. A. Paine Eds. *Sustainable Construction: Use of Incinerator Ash*. London: Thomas Telford, 1-17.

PWMI (2001). "*LCA survey and research report on treatment and disposal of plastic waste*." Plastic Waste Management Institute. (in Japanese)

Sano, S. *et al*. (2000). "Eco-balance of filler cement and concrete." *Journal of Research of the Taiheiyo Cement Corporation*, 138, 16-23. (in Japanese)

Shima, H., Tateyashiki, H., Hashimoto, K. and Nishimura, Y. (2001). "Life cycle assessment of high quality aggregate recovery from demolished concrete with heating and rubbing method." *Proceeding of the Japan Concrete Institute*, 23 (2), 67-72. (in Japanese)

Shima, H., Tateyashiki, H., Matsuhashi, R. and Yoshida, Y. (2005). "An advanced concrete recycling technology and its applicability assessment through input-output analysis." *Journal of Advanced Concrete Technology*, 3 (1), 53-67.

Shimoda, T. and Yokoyama, S. (1999). "Eco-cement: A new portland cement to solve municipal and industrial waste problems." *In:* R. K. Dhir and T. D. Dyer, Eds. *Proceedings of the International Conference held at the University of Dundee*, Dundee *September 1999*. 17-30.

Tamashige, T. *et al*. (1992). "Operating results of a newly designed air classifier for fly ash." *The Cement Manufacturing Technology Symposium*, 49, 52-57. (In Japanese)

Uchida, S. (1991). "Manufacture and use of blast furnace slag cement." *Journal of Research of the Onoda Cement Company*, 43 (124), 56-79. (In Japanese)

Yamamoto, K., Morioka, M., Watanabe, Y. and Sakai, E. (1999). "Effect of high strength additive for reduction of environmental loading." *Proceedings of the Japan Concrete Institute*, 21 (2), 1141-1146. (in Japanese)

Yamamoto, K., Morioka, M., Watanabe, Y., Sakai, E. and Daimon, M. (2002). "Effect of high strength additive on reduction of environmental burden." *In: 5th International Symposium on Cement and Concrete*, Shanghai *28 October - 1 November 2002*. 618-623.