Quantitative Assessment of Environmental Impacts on Life Cycle of Highways

Kwangho Park[1]; Yongwoo Hwang[2]; Seongwon Seo, M.ASCE[3]; and Hyungjoon Seo[4]

Abstract: Several representative environmental loads emitted from the life cycle of highways, which form one of the major infrastructure sectors, were estimated. The life cycle of highways was divided into four stages—manufacturing of construction materials, construction, maintenance/repair, and the demolition/recycling stage. Energy consumption in each life cycle stage was quantified, and environmental load was estimated by applying the environmental emissions factor per each energy source. As a result, it is estimated that the most energy was consumed in the manufacturing stage of construction materials, with consumption of 1,525.8 tons of oil equivalent (TOE) per functional unit (1 km and four lanes of highway). Energy consumption in the maintenance and repair stage was also relatively high among the life cycle stages; the next highest consumption was for the construction and demolition stage. Through the whole life cycle of 20 years, 2,676.8 TOE of energy per functional unit was consumed, and this corresponds to SO_2, NO_x, and CO_2 emissions of 62.1 tons, 17.1 tons, and 2,438.5 T-C, respectively.

DOI: 10.1061/(ASCE)0733-9364(2003)129:1(25)

CE Database keywords: Environmental impacts; Life cycles; Highways.

Introduction

Public awareness of global environmental problems such as global warming and ozone depletion has increased, to become one of the biggest issues for the new millennium, since the concept of sustainable development has attracted public attention as the greatest concern of the late twentieth century. According to this concern, some action and counterplanning to solve the regional and global environmental problems have occurred. As part of these efforts, several international environment conventions have been conducted, and their final goals are focused on the reduction of fossil energy consumption and development of alternative energy (Ministry of Trade and Industry 1997; Harris 1999). It is viewed, therefore, that sooner or later every country in the world should take part in international agreements voluntarily because they are essential in dealing with the global environmental problems, even though the socioeconomic situation of each country is different. In the case of Korea, its energy dependence on foreign supplies is over 90%; thus, it is clear that all industries are affected, and the construction industry is not an exception (Seo et al. 1999; Hwang 2000; Seo and Gee 2000).

By its very nature, construction involves manipulation and use of large quantities of natural and man-made materials. Also, the construction and operations of infrastructure are large users of energy. As a result, it is a critical industry for the study of industrial ecology, the systematic analysis of resource and energy flows within the anthroposphere, and the realm of man-made or managed resources (Graedel and Allenby 1995). With increased attention to issues of sustainable development, the industrial ecology of construction is a subject of considerable interest worldwide (Hendrickson and Horvath 2000).

The wide variety of materials used in construction work, as well as fuel and electricity used for construction machinery and recycling plants have a significant environmental impact. In this study, the life cycle assessment (LCA) method for the highway life cycle is described. The energy requirement and environmental loads for construction, repair, demolition, and recycling of highways were assessed, and the LCA can therefore be used as a design tool in the pursuit of more environmentally sound alternatives.

Methods

LCA is a method for analyzing and assessing the environmental impact of a material, product, or service throughout its entire life cycle, usually from the acquisition of raw materials to final disposal. Traditionally, the main focus in LCA has been on the regional and global environmental impacts on the external environment. The environmental impacts include emissions to air, discharges into water, and the generation of solid wastes (International 1997). In this study, aimed at the recently emerging global warming problem, the atmospheric environmental loads due to energy consumed through the life cycle of highways were chosen as the items to be assessed.

---

[1] PhD Candidate, Dept. of Environmental Engineering, Inha Univ., 253 Yonghyun-Dong, Nam-Ku, Inchon 402-751, Korea. E-mail: g2001351@inhavision.inha.ac.kr

[2] Associate Professor, Dept. of Environmental Engineering, Inha Univ., 253 Yonghyun-Dong, Nam-Ku, Inchon 402-751, Korea.

[3] COE Research Fellow, Division of Urban Environmental Systems, Research Center for Advanced Science and Technology, Univ. of Tokyo, 4-6-1, Komaba, Meguro-ku, Tokyo 153, Japan.

[4] Professor, Dept. of Environmental Engineering, Inha Univ., 253 Yonghyun-Dong, Nam-Ku, Inchon 402-751, Korea.

Note. Discussion open until July 1, 2003. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on December 6, 2000; approved on February 15, 2002. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 129, No. 1, February 1, 2003. ©ASCE, ISSN 0733-9364/2003/1-25–31/$18.00.

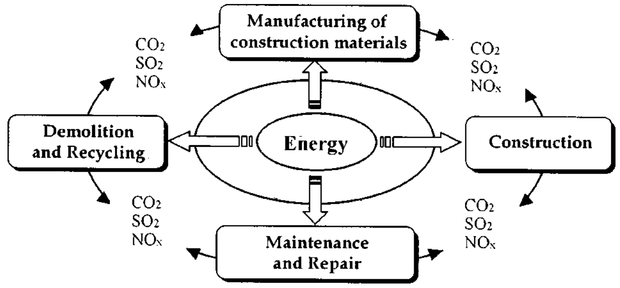

Fig. 1. Life cycle of highways and system boundary

In general, LCA is composed of the following four steps: goal definition and scope, inventory analysis, impact analysis, and improvement assessment (Curran 1996; International 1997). Of these, an impact analysis that evaluates many different environmental loads with the same estimating index is very difficult and near to ideal. Therefore, this has not been established yet in LCA methodology. Thus, current LCA is mainly performed with an inventory analysis, which calculates the environmental loads generated from the initial step of getting raw materials to the final step of waste production, in the form of a detailed inventory table. In this study, also, the life cycle inventory analysis of highways was mainly analyzed.

There are two forms of life cycle inventory analysis methods to quantify environmental loads—process analysis and input-output (IO) analysis. Process analysis for totaling environmental loads in every stage of the life cycle has been applied to analyze individual products and materials. Otherwise, IO analysis, which is based on Leontief's mathematical model, has been applied for macroobjects such as urban systems (Hwang et al. 1996a,b). In this study, a hybrid analysis combining the previous two analysis methods was applied. As the functional unit (FU) of the estimation, 1 km of a four lane highway was chosen. The life cycle of highways and the system boundary of this study are shown in Fig. 1. Of these stages, the construction stage is divided into earth, drainage, pavement, and appurtenant work.

Manufacturing Stage of Construction Materials

IO analysis provides a useful framework for tracing energy use and other activities, such as environmental pollution associated with interindustry activities. In recent years, much attention has been focused on extending the Leontief IO framework to account for such activities (Miller and Blair 1985). In this study, an energy IO (EIO) analysis was used to quantify energy consumption by manufacturing construction materials input in constructing highways. That is, energy consumption of construction materials was estimated using 1995 IO tables (*1995 Input* 1998) and the energy balance table of Korea (Korea 1996). Then, by applying the average price of construction materials to the estimated values, as shown in Table 1, the energy consumption per each unit (m^3, ton, EA, etc.) was quantified.

Construction Stage

Most construction activities are carried out with heavy machinery. In the process of construction, energy is directly consumed by using construction machinery. Energy consumption of construction machinery can vary according to the scale, the deterioration of machinery, and the skill of the operators. In this study, we used previously investigated data in Korea (Hwang et al. 2000) for working quantity and fuel consumption of construction machinery, as reported in Table 2.

Table 1. Energy Consumption for Manufacturing Major Construction Materials

Type of materials	Direct	Total	Unit
(a) Steel manufacturing			
Steel bar	0.02670	0.39767	ton
Cold rolled steel sheet	0.01963	0.37705	ton
Hot rolled steel sheet	0.01758	0.43702	ton
Structural steel pipe	0.00002	0.00055	m
(b) Aggregates and cement			
Sand	0.00040	0.00075	m^3
Gravel	0.00045	0.00084	m^3
Crushed stone	0.00240	0.00341	m^3
Ready-mixed concrete	0.00277	0.02597	m^3
Cement	0.04568	0.06619	ton
Concrete block	0.00019	0.00118	EA
(c) Wood manufacturing			
Lumber	0.00024	0.00624	m^3
Timber	0.00707	0.03136	m^3
(d) Materials for pavement			
Asphalt concrete	0.00413	0.01222	ton
Straight asphalt	0.02478	0.07331	ton
Lime powder	0.01190	0.02051	ton
Expansion joint filler	0.00051	0.00485	m
Guardrail	0.00112	0.01063	EA
Light-shielding net	0.00278	0.02636	EA
Soundproofing wall	0.00783	0.07414	EA
Delinator	0.00026	0.00242	EA

Note: TOE = tons of oil equivalent.

Maintenance and Repair Stage

Maintenance and repair of highways include surface repair, structure repair, damaged road repair, and retarring of damaged land.

Table 2. Energy Consumption for Operating Construction Machinery (10^{-3} TOE/Q^a)

Type of machinery	Energy consumption
Concrete mixer truck	2.32479
Dump truck (15 ton)	2.02208
Concrete finisher	1.05978
Concrete pump car	0.69000
Bulldozer (32 ton)	0.34753
Concrete cutter	0.15493
Tire pay loader	0.14453
Rammer	0.13265
Backhoe (0.7 m^3)	0.11383
Water tank	0.11138
Motor grader	0.09799
Asphalt paver	0.07162
Vibrating roller	0.05799
Tire roller	0.04523

[a] Q = working quantity per each type of machinery.

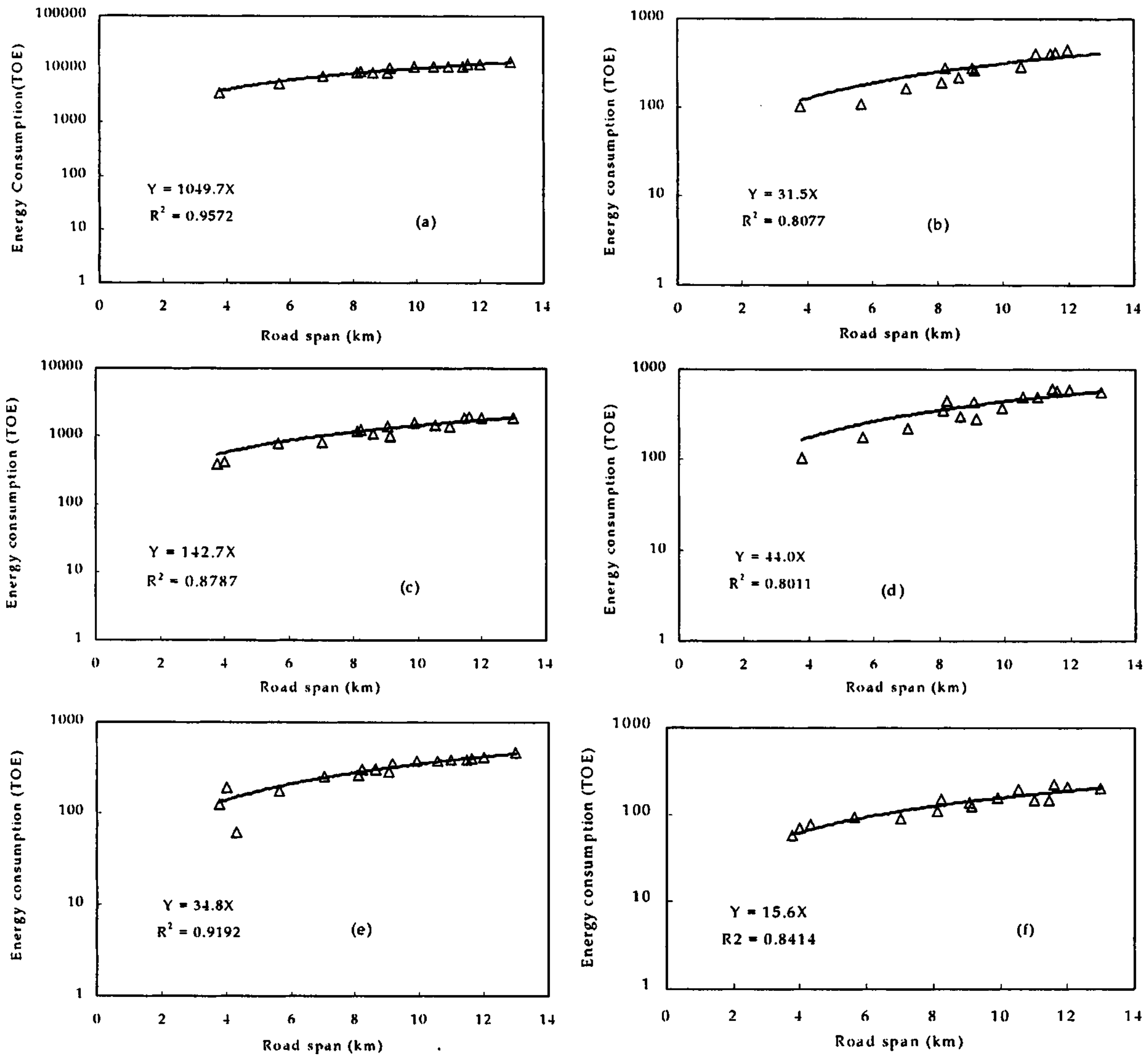

Fig. 2. Correlation of energy consumption of construction materials and road span (*Y*-axis is log scaled):(a) cement; (b) asphalt concrete; (c) steel bar; (d) ready-mixed concrete; (e) crushed stone; (f) gravel

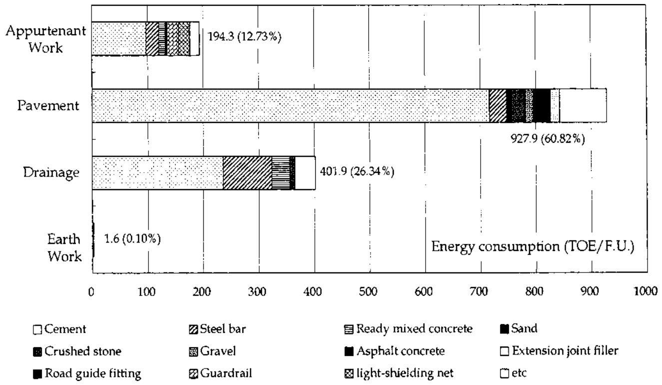

Fig. 3. Energy consumption for manufacturing of road construction materials

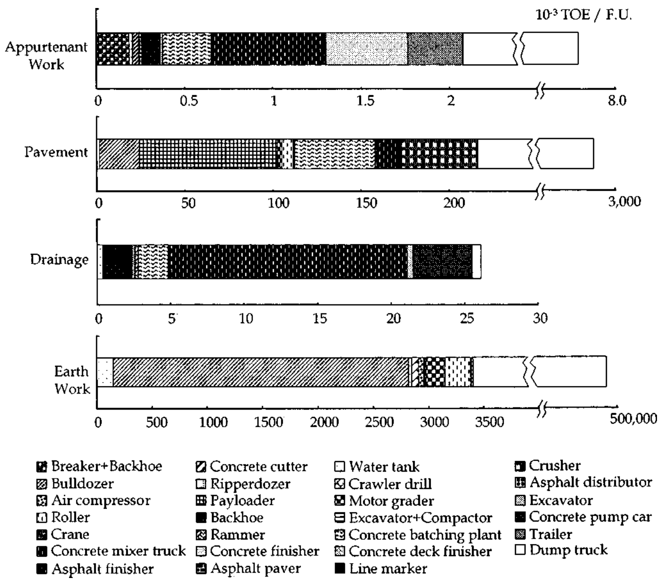

Fig. 4. Energy consumption of construction machinery

Table 3. Energy Consumption of Milling-overlay Pavement and Repavement (1,300 won/U.S. Dollar)

Process	Energy consumption
Milling-overlay pavement	0.3095[a]
Milling-overlay pavement	69.3[b]
Repavement	2.71[c]
Repavement	930.6[d]

Note: For milling-overlay pavement, construction expenses = 56 million won/km · lane. For repavement, energy consumption by manufacturing of construction materials = 927.9.

[a] TOE/million won.

[b] TOE/FU.

[c] Energy consumption of construction machinery.

[d] TOE/FU.

Of these, we only considered surface repair such as surface treatment, overlay, and repavement, because the other repairs pose difficulties in the determination of the repair period. They also require lower energy consumption than pavement repair.

It is very important to maintain and repair road pavement intentionally, after investigating the road surface with measuring instruments and then evaluating it. Maintenance and repair of highways are carried out with a pavement level termination method such as the present serviceability index in the United States, the maintenance control index in Japan, and the pavement management system in Korea (*Guidebook* 1999). However, the life span as well as the repair period of infrastructure including highways may be lengthened or shortened because of the varied geographical, social, and economical conditions in which the infrastructure is located. Practically, it is difficult to determine the life span and repair period, and some statistical models were often used (Seo and Hwang 1999). In this paper, the repair period of the pavement was assumed to be seven years, and the life span, 20 years, throughout the questionnaire, completed by experts of the concerned organizations. Finally, it was assumed that the pavement of highways is repaired by milling-overlay pavement once every seven years, and repaved every 20 years after being repaired twice. In addition, every one lane of pavement is in turn repaired to prevent traffic problems; this is defined as milling-overlay pavement.

Demolition and Recycling Stage

Generally, highways are demolished after their life span, and then construction and demolition (C&D) debris generated from highways is transported to reclaimed land or recycling plants. Energy is consumed by using fuel and electric power in the process of transporting and recycling. In the demolition and recycling stages of highways, this energy consumption is estimated.

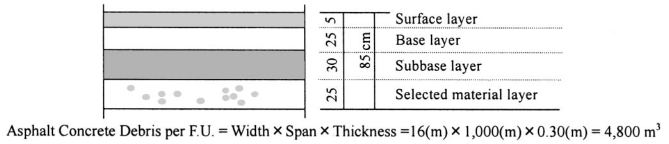

Fig. 5. Cross section of asphalt concrete pavement

Table 4. Energy Consumption at Highway Demolition

Parameter	Value
Machinery	Breaker + backhoe
Working quantity (m^3/h)	5.75
Fuel consumption[a] (L/h)	24.4
Petroleum conversion factor (TOE/L)	0.00092
Quantity of C&D (m^3/FU)	4,800
Energy consumption (TOE/FU)	18.7

[a] Energy source is diesel.

Results and Discussion

Energy Consumption in Construction Materials Manufacturing Stage

It is difficult to determine clearly the materials demand input to the construction of highways because the materials demand may vary due to the preference of the ordering company and the ground conditions on-site. Accordingly, we selected general sections of actual highways available to the public, and then collected data about the construction materials demand using the bill of quantity and unit cost (Korea 1997a,b). First, for analyzing the correlation between the road span (independent variable) and energy consumption of construction materials (dependent variable), which is estimated in this paper, we took out a regression model formula with collected data. The coefficient of determination R^2 between the road span and energy consumption of construction materials presented a strong positive linear relationship (higher than 0.8), as shown in Fig. 2. The regression formula of Fig. 2 is linear. The scale of the Y-axis is so huge that we took the log-scaled axis. The result demonstrates that energy consumption increases in proportion to the increase of the road span. On the other hand, an intercept of the dependent variable (energy consumption of construction materials) was employed as "zero," assuming that there is no energy used before construction of the highway.

Energy consumed in the manufacturing stage of construction materials is presented in Fig. 3. Considered in every construction material, energy consumed for the manufacturing of cement and steel bars is the highest, with 1,049.7 tons of oil equivalent (TOE) and 142.7 TOE, with a total of 1,525.7 TOE. In each case of construction work, energy consumption took up a major portion in the pavement work, with 927.9 TOE (60.82%). The next was drainage, appurtenant work, and earth work, in this order. This is mostly caused by the material demand in pavement work. Meanwhile, the energy used in earth work is at a low level, about 0.1%, because sand and crushed stones are of little input.

Energy Consumption of Construction Machinery

The working quantity of construction machinery used on-site can vary, even though the same machinery is used, according to construction work. Consequently, it is necessary to understand how many machines are used in each phase of construction work—

Table 5. Energy Consumption of C&D Debris Transportation

Parameter	When disposed	When recycled
Energy intensity (TOE/ton)	0.0015	0.0015
Quantity of C&D (ton/FU)	6,864	3,696
Energy consumption (TOE/FU)	10.3	5.5

Table 6. Energy Consumption of Machinery for Recycling of C&D Debris

Parameter	Backhoe ($1\ m^3$)	Crusher ($1\ m^3$)	Loader ($5\ m^3$)	Total
Requirement	2	2	2	6
Operating hour (h/day)	8	8	8	—
Fuel consumption (L/h)	17.7	17.7	36.2	71.6
Energy consumption (L)	283.2	283.2	579.2	1,145.6

namely, earth work, drainage, paving, and appurtenant work—and how much energy is consumed in the total work. In this paper, the working quantity of machinery, used in highway construction, was calculated by using the bill of quantity and unit cost (Korea 1997a,b). Applying these results to energy consumption per unit of working quantity, energy consumption of the operating construction machinery was estimated. In Fig. 4, energy consumption of a dump truck formed 92.7%. Similarly, earth work, in which a dump truck is used most often, held 94.5% of the total life cycle. Through these results, the efficient management of dump trucks might produce a considerable effect on the reduction of energy consumption of construction machinery.

Energy Consumption of Maintenance and Repair Stage

EIO analysis was used to estimate the energy consumed in repairing the pavement of highways and the construction cost of milling-overlay pavement per 1 km of highway span (Korea 1999). Energy consumption for the repavement was estimated by applying the data for materials and machinery utilized in the manufacturing and construction stage. The results reported in Table 3 demonstrate that 1,069.2 TOE per FU (69.3 TOE×2 +930.6 TOE) is consumed to maintain and repair highways for 20 years.

Energy Consumption in Demolition Stage

Generally, the cross section shown in Fig. 5 is applied for highways, especially asphalt concrete pavement. From this structure of the pavement, we are able to estimate the amount of C&D debris generated in the demolition stage.

Energy consumption of construction machinery input in the demolition of highways was estimated by applying the fuel demand and the working quantity of machinery. Similarly, the energy demand for demolishing highways and transport of waste was estimated by applying the mentioned quantity of C&D debris. As shown in Table 4, 18.7 TOE/FU of energy was consumed in demolishing highways.

After demolition, the C&D debris is either recycled or disposed of. In this study, according to the recycling goal of the Korean government for C&D debris, it is assumed that 35% (3,696 tons, 1,680 m^3) of C&D debris generated is recycled, and the other 65% (6,864 tons, 3,120 m^3) is sent to reclaimed land. Also, it was assumed that 0.0015 TOE is required to transport 1 ton of C&D debris, using previous data from a Korean study (Seo 1998). Transportation energy for recycling and landfill as shown in Table 5 was estimated by applying the allocated C&D debris and energy intensity per unit weight of C&D debris.

Table 7. Energy Consumption of Recycling Plant

Parameter	Value
Working days per month	25
Electricity consumption (kW/month)	97,529.96
Energy consumption (kW/day)	3,901.6

Table 8. Energy Consumption of Recycling of C&D Debris

Parameter	Machinery	Recycling plant
Quantity of C&D (ton/FU)	3,696	3,696
Energy intensity (TOE/ton)	0.00058	0.00019
Energy consumption (TOE/FU)	2.1	0.7

Note: Total energy consumption=2.1+0.7=2.8.

Energy Consumption in Recycling Stage of C&D Debris

C&D debris is reproduced throughout several recycling processes such as crushing, classifying, and screening. Energy consumed in the recycling stage includes fuel demand for heavy machinery and electric power demand for the recycling plant. The former is estimated by using the fuel consumption data of machinery, and the latter, by converting electricity to energy units. These data were collected from a questionnaire that was distributed to a recycling corporation in Korea (Tables 6 and 7).

1,800 tons of C&D debris/day is input in a recycling process, assuming that the input quantity per day of the recycling plant is 225 tons and operation hours are 8 h/day. The energy consumption to recycle 1 ton of C&D debris was estimated by applying the fuel consumption of the machinery and the electricity consumption of the recycling plant to a petroleum conversion factor. As a result, 0.00019 TOE was consumed in the recycling plants for the recycling of 1 ton of C&D debris, as reported in Table 8.

In summary, 3,696 tons of C&D debris can be recycled, assuming that 35% of C&D debris is recycled. Applying 3,696 tons of C&D debris to the energy consumption intensity of the construction machinery and the recycling plant, 2.8 TOE in total is consumed in recycling.

Energy Reduction Effects of Recycling C&D Debris

The energy reduction effects in the case of C&D debris recycling are considered with two life cycle systems illustrated in Fig. 6. Recycled materials of C&D debris in Korea are used for the rehabilitation and repair of construction at the base and subbase layers of highways after recycling. In this paper, we examine the energy reduction effects in the case where all recycled materials are used for the subbase layer of highways. Namely, C&D debris

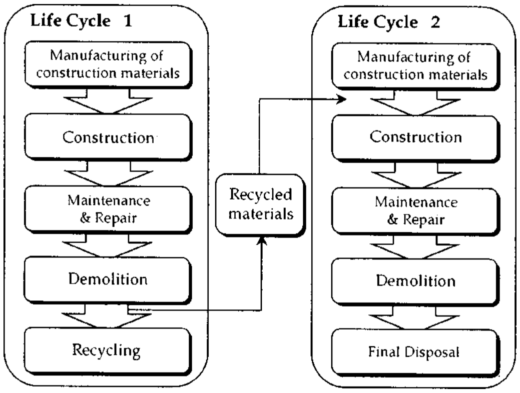

Fig. 6. Life-cycle system of highways

Table 9. Energy Reduction Effects due to Recycling of C&D Debris (TOE/FU)

Process	Value
(a) Energy consumption (Life cycle 1)	
Manufacturing of construction materials	1,525.7
Construction	47.1
Maintenance and repair	1,069.4
Demolition	18.7
Recycling[a]	39.8
[Total]	2,700.7
(b) Energy consumption (Life cycle 2)	
Manufacturing of construction materials[b]	1,480.7
Construction	47.1
Maintenance and repair	1,069.4
Demolition[c]	34.5
[Total]	2,631.7

[a] Including double transportation energy 31.6 TOE (on-site →recycling plant→on-site).

[b] Excluding energy consumption, 45 TOE (11+34), for manufacturing of sand and crushed stone.

[c] Including transportation energy 15.8 TOE.

is transported to the recycling plant, passes through the recycling process, and then is used for the subbase layer in other construction sites. To understand clearly the energy reduction effects, the recycling percentage of C&D debris is assumed to be 100%. This assumes that there will be further technological developments in recycling.

The subbase layer of highways generally consists of sand and crushed stones. Energy consumption in the recycling stage can be estimated by adding up the transportation energy for C&D debris and the energy used in the recycling plant. Finally, when recycled C&D debris, such as sand and crushed stones, is used for the subbase layer, the energy consumed in the manufacturing stage of such materials is not required in highways where recycled aggregate is utilized. If 4,800 m^3 of C&D debris in Life cycle 1 of Fig. 6 is recycled and the recycled materials are used for the subbase layer, 45 TOE (sand, 11 TOE+crushed stone, 34 TOE) of energy can be saved. Here, 39.8 TOE (energy consumption in the recycling plant, 8.2 TOE+double transportation energy, 15.8×2 TOE) consumed for recycling should be considered. In the case where the recycling process is included in Life cycle 1, energy reduction effects in Life cycle 2 are presented in Table 9.

Table 10. Environmental Emission Units of Each Energy Source

Energy source	Oxidation ratio[a]	Petroleum conversion factor (TOE)[a]	NO_X (kg/TOE)[a]	SO_2 (kg/TOE)[a]	CO_2 (kg/TOE)[a]
Anthracite	0.980	0.00054	7.63	27.66	1,100
Bituminous coal	0.980	0.00066	7.35	26.63	1,059
Naphtha	0.990	0.00080	5.75	20.84	829
Gasoline	0.990	0.00083	5.49	19.91	792
Jet oil	0.990	0.00087	5.60	20.32	808
Kerosene	0.990	0.00087	5.63	20.42	812
Diesel	0.990	0.00092	5.81	21.05	837
Heavy oil	0.990	0.00097	6.07	22.00	875
LPG	0.990	0.00012	4.95	17.93	713
Electricity	0.998	0.00009	6.26	22.68	902
City gas	0.995	0.00105	4.42	16.02	637

[a] Emission factor.

Table 11. Environmental Load through Life Cycle of Highways

Process	Energy (TOE/FU)	NO_X (ton/FU)	SO_2 (ton/FU)	CO_2 (T-C/FU)
Manufacturing of construction materials	1,525.7	9.8	35.4	1,391.4
Construction	47.1	0.3	1.1	41.7
Maintenance and repair	1,069.4	6.8	24.8	976.5
Demolition	34.5	0.2	0.8	28.9
[Total]	2,676.7	17.1	62.1	2,438.5

Environmental Loads through Life Cycle of Highways

Environmental loads are estimated by applying energy consumption, estimated in each stage, to the environmental emissions factor. The environmental emissions factor can vary according to the oxidation ratio of each energy source, by how many contaminants are included, and where they are to be used. However, there is no environmental emissions factor published so far in Korea. Additionally, environmental problems caused by energy consumption are not regional, but global. In this study, therefore, the environmental emissions factor presented by the Intergovernmental Panel on Climate Changes, as noted in Table 10, is utilized to evaluate environmental loads objectively.

Total energy consumption through the life cycle of highways, as shown in Table 11, was 2,676.7 TOE/FU. Of this, 1,525.7 TOE (56.9% of total consumption) was consumed in the manufacturing stage of construction materials. According to the results, it is found that the energy consumed directly and indirectly in the process of manufacturing is the greatest part of the total life cycle. On the other hand, environmental loads, estimated by applying the environmental emissions factor per each energy source, in every stage of the highways followed the same pattern. NO_x, SO_2, and CO_2 emissions in the manufacturing stage of materials were 9.8 tons, 35.4 tons, and 1,391.4 T-C, respectively. Next was the maintenance and repair stage (39.9%), followed by construction (1.9%), and finally the demolition stage (1.3%).

Conclusion

Though infrastructure including highways poses a major part of national energy consumption and is closely tied to human beings, it is not understood as a whole how much it affects the environment. In this study, energy consumption and several related environmental loads generated from the whole life cycle of highways including the manufacturing of materials, construction, maintenance/repair, and demolition/recycling are quantified using the LCA method. In the results, NO_x, SO_2, and CO_2 emissions were 17.1 tons, 62.1 tons, and 2,438.5 T-C, respectively, consuming 2,676.7 TOE per FU.

There are some assumptions for the purpose of generalized evaluation. This is indispensable to assess systems such as highways including compound elements. Because the study was evaluated using generalized conditions, the results of this paper can be simply applied to the specific situations in order to translate the results to other regions of the world. In the meantime, there are no data in Korea to compare with the energy intensity estimated in this study. Therefore, more case studies to evaluate infrastructures are recommended.

Acknowledgment

This work was supported by an INHA University Research Grant (INHA-21359).

References

Curran, M. A. (1996). *Environmental life-cycle assessment*, McGraw-Hill, New York.

Graedel, T. E., and Allenby, B. (1995). *Industrial ecology*, Prentice-Hall, Englewood Cliffs, N.J.

Guidebook to maintain and repair road pavement. (1999). Department of Road Management, Ministry of Construction and Transportation, Korea (in Korean).

Harris, D. J. (1999). ''A quantitative approach to the assessment of the environmental impact of building materials.'' *Build. Environ.*, 34, 751–758.

Hendrickson, C., and Horvath, A. (2000). ''Resource use and environmental emissions of U.S. construction sectors.'' *J. Constr. Eng. Manage.*, 126(1), 38–44.

Hwang, Y. (2000). ''Necessity of LCA to evaluate systematic environmental load in construction industry.'' *J. Kor. Soc. Civ. Eng.*, 48(1), 13–18 (in Korean).

Hwang, Y., Hanaki, K., and Tanaka, T. (1996a). ''Consideration of life cycle CO_2 on sludge treatment system.'' *J. Japan Sewage Works Association*, 33, 75–87 (in Japanese).

Hwang, Y., Hanaki, K., and Tanaka, T. (1996b). ''Effective energy utilization in sludge treatment system.'' *Envir. Syst. Res.*, 24, 703–708 (in Japanese).

Hwang, Y., Park, K., and Seo, S. (2000). ''Assessment of CO_2 emissions from road construction activities.'' *J. Kor. Soc. Civ. Eng.*, 20(1-B), 113–121 (in Korean).

International Standards Organization (ISO). (1997). ''Environmental management—Life cycle assessment—Principles and framework.'' *Draft International Standard 14040*, Geneva.

Korea Energy Economics Institute (KEEI). (1996). ''Energy balances of Korea (1981–1996).'' *Rep.*, Ministry of Trade and Industry, Korea (in Korean).

Korea Highway Corporation (KHC). (1997a). ''Bill of quantity for highway construction work.'' *Rep.* (in Korean).

Korea Highway Corporation (KHC). (1997b). ''Bill of unit cost for highway construction work.'' *Rep.* (in Korean).

Korea Highway Corporation (KHC). (1999). ''Bill of unit cost for maintenance and repair of highway.'' *Rep.* (in Korean).

Miller, R. E., and Blair, P. D. (1985). *Input-output analysis: Foundations and extensions*, Prentice-Hall, Englewood Cliffs, N.J.

Ministry of Trade and Industry. (1997). ''A pilot study for the development of energy life cycle inventory methodology.'' *Korea Governmental Rep.* (in Korean).

1995 Input-output tables (CD-Rom). (1998). The Bank of Korea (in Korean).

Seo, S. (1998). ''Assessment of life cycle carbon dioxide emission for residential building and development of the calculating system.'' PhD thesis, Dept. of Civil Engineering, Chungang Univ., Seoul, Korea (in Korean).

Seo, S., and Gee, J. (2000). ''Methodology to apply LCA to construction industry.'' *J. Kor. Soc. Civ. Eng.*, 48(1), 19–26 (in Korean).

Seo, S., and Hwang, Y. (1999). ''An estimation of construction and demolition debris in Seoul, Korea: Waste amount, type, and estimating model.'' *J. Air Waste Manage. Assoc.*, 49(8), 980–985.

Seo, S., Hwang, Y., and Ichinose, T. (1999). ''Development and application of calculating system for evaluation of life cycle CO_2 emission of construction building.'' *J. Kor. Soc. Civ. Eng.*, 19(II-6), 749–755 (in Korean).