An Advanced Concrete Recycling Technology and its Applicability Assessment through Input-Output Analysis

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Abstract

While at present mostly recycled into road subbase, the amount of demolished concrete in Japan is expected to increase rapidly and exceed the demand for road subbase in the near future. To promote the recycling of concrete, a technology to produce high-quality recycled aggregate has been developed. This technology employs the heating and rubbing method. In order to investigate a future concrete recycling system, first of all, a specific model considering indices of economic activity is established to forecast the amount of demolished concrete in the future. Furthermore, an input-output table is extended by a detailed description of concrete-related industries such as construction, aggregate, cement, and ready-mixed concrete, and several concrete recycling processes have been added. The linear programming model connected to the input-output table assumes that the technology will be introduced in 2020. A subsidy for high-quality recycled aggregate and a carbon tax are found to be effective ways to promote the early introduction of the technology. This series of analysis can be widely used in other countries for investigating suitable recycling systems focusing on the cement and concrete industry as well as the applicability of each individual concrete recycling technology.

1. Introduction

Concrete is widely used as a basic material for construction and infrastructure. Approximately 500 million tons of concrete were produced in Japan around 1990. In recent years, approximately 35 million tons of demolished concrete are being generated every year. Actually, this figure might be an underestimate partly because some concrete is illegally dumped or mixed with construction soil that is not treated as waste. 95% of the concrete is recycled using cascade recycling and subsequently reused as low-quality road subbase. High-quality level recycling in which recycled aggregate is made from concrete, is not carried out at present.

In the near future, a substantial amount of concrete from construction undertaken during the economic growth of the 1960s and 1970s will reach its end of life, and the generation of demolished concrete is expected to rapidly increase.

We have developed a technology to produce high-quality aggregate from demolished concrete using a 'heating and rubbing method' (HRM) (Shima 1999, Shima 2000). Using this technology, aggregate can be recycled as raw material for ready-mixed concrete, while fine powder (HRM powder) from cement paste can be recycled as raw material for cement, cement admixture, or soil stabiliser. We propose that this technology be used in a level concrete recycling system (**Fig. 1**).

While the production of recycled aggregate using the HRM consumes much fuel for heating and electricity for rubbing, our life-cycle analysis showed that the use of the HRM can reduce CO_2 emissions through the utilisation of the HRM powder as cement-related inputs as mentioned above (Shima 2003a, Shima 2004a).

Many studies dealing with technologies for producing recycled aggregate and their life-cycle analysis have been carried out in Japan. However, there are currently no studies that attempt to forecast future trends in the amount of demolished concrete, or to analyse the future

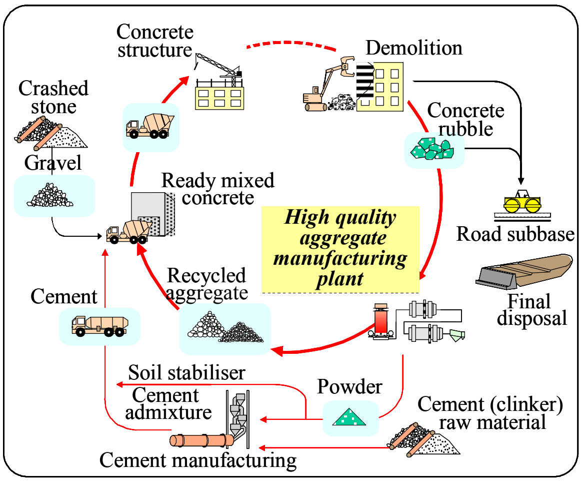

Fig. 1 Schematic flow of concrete recycling system.

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role of advanced concrete recycling systems. This study aims at filling this gap.

Input-output analysis is widely used in economics for determining the economy-wide repercussions due to a final demand stimulus. In this paper, an input-output table is extended by a detailed description of concrete-related industries such as construction, aggregate, cement, and ready-mixed concrete, as well as by several concrete recycling processes such as the HRM, low-quality recycled aggregate production, and road subbase production. The future concrete recycling system and the possibility of the introduction of concrete recycling by the HRM is investigated using a linear programming model connected to the extended input-output table.

2. HRM: a novel technology for producing high-quality recycled aggregate

2.1 High-quality recycled aggregate producing process

In the HRM, when demolished concrete is heated to approximately 300°C, the cement paste is made brittle by dehydration. To remove the cement paste from the surface of aggregate, the heated concrete is rubbed in a mill by media. **Figure 2** shows the effect of the heating temperature on the quality of the coarse aggregate treated using this method. The effect is almost saturated at approximately 300°C. Therefore, 300°C is chosen as the heating temperature. Koga et al. confirmed that the qualities of aggregate heated up to 500°C do not deteriorate by examining the changes in density, absorption, etc. (Koga 1997). **Figure 3** shows the oven-dry density and absorption of the recycled coarse aggregate and the recovery ratio to the original aggregate at each quality level as the result of an experiment using laboratory scale apparatus. The degree of rubbing treatment varied according to the change in amount of media or rotational velocity of the mill. There is a linear relationship between the oven-dry density and absorption. The recovery ratio decreases as the oven-dry density increases and absorption decreases. This implies that the amount of adhesive mortar or cement, which determines the quality of aggregate, is changed by the degree of rubbing treatment. Therefore, the quality of aggregate can be controlled by changing the amount of media or the rotational velocity of the mill.

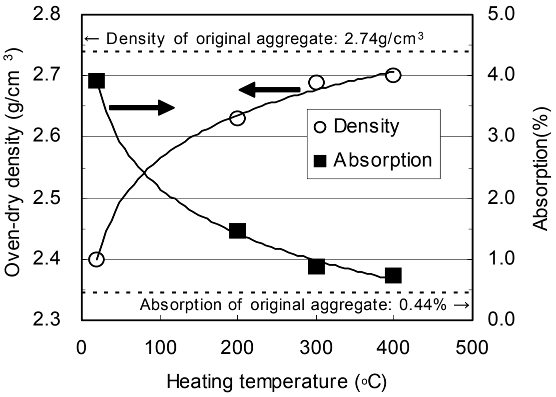


Fig. 2 Effect of heating temperature on qualities of recycled coarse aggregate.

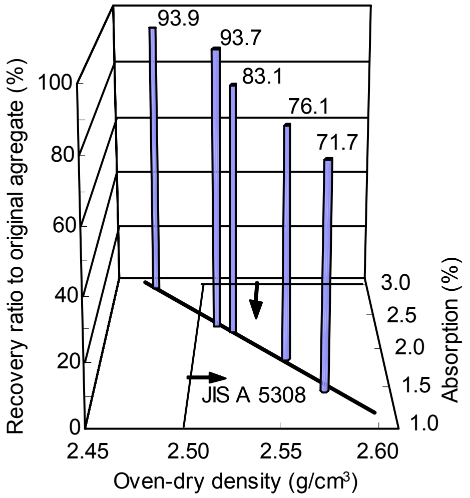


Fig. 3 Relation between oven-dry density and absorption and recovery ratio at each quality level.

The Results of aggregate recovering tests using laboratory scale apparatus and a 300 kg/hr pilot plant showed that both coarse and fine aggregates meeting the standard of normal aggregates prescribed by the Japanese Industrial Standard 'Ready-mixed concrete JIS A 5308' could be recovered at a high ratio (Tomosawa 1998). Based on these achievements, a portable test plant for recovering high-quality aggregate with a capacity of 5t/hr was developed (Shima 2000). This plant is composed of approximately 20 portable units. These units can be separated to allow easy transportation on a trailer and reassembled at the collection site of the demolished concrete. **Figure 4** shows the whole view of the plant.

Figure 5 shows the process flow of the plant. The concrete rubble crushed to a size under 50 mm is heated to 300°C in a vertical kerosene-fuelled furnace. The heated concrete is sent to primary rubbing equipment. The equipment is a tube type mill with inner and outer

Fig. 4 Whole view of portable pilot plant.

cylinders. In the equipment, the heated concrete is rubbed by steel balls as media and the generated mortar portion is discharged through the screen provided on the inner cylinder to increase the efficiency of rubbing treatment. Then, the coarse aggregate and the removed mortar are sent into the secondary rubbing equipment in which the cement adhering to the fine aggregate is removed by the coarse aggregate as media. All the aggregate from the secondary equipment is fed into a 5mm vibrating screen and separated into coarse and fine aggregate. The fine powder generated in the secondary equipment is swept by air and collected in a bag filter. The average ratios of aggregate recovery and fine powder generation to the original concrete in terms of weight are 35% of coarse aggregate, 30% of fine aggregate, and 35% of fine powder, respectively. Based on the field test using the portable plant, a commercial portable plant with capacity of 10 ton/hr was designed and constructed, and used for two large-scale building reconstructions.

2.2 Quality of recycled aggregate and its concrete

The quality of the aggregate recycled using the HRM meets the JIS A 5308 standard. The performance of the HRM-recycled aggregate concrete is comparable to that of ordinary concrete as demonstrated by a series of tests (Tateyashiki 2001). Furthermore, the aggregate has been applied in several concrete buildings. In these cases, the properties of strength and durability were the same as those of normal concrete, and pumpability and castability were also satisfactory (Kuroda 2001, 2002, Nakato 2001).

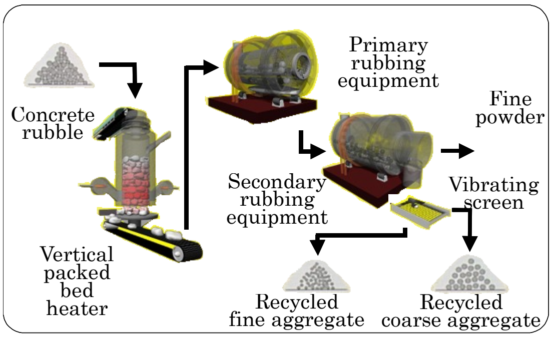


Fig. 5 Process flow of high-quality recycled aggregate manufacturing process.

2.3 Usage of HRM powder

We have examined the properties of the HRM powder and proved that its ability to absorb water makes it suitable as a soil stabiliser (Shima 2004a). We also verified using a concrete performance test that blast furnace slag cement (BFSC) containing 10% of HRM powder could be used as ordinary BFSC (Shima 2004b).

2.4 Life cycle energy and CO_2 of high quality recycled aggregate by HRM

The HRM uses a considerable amount of energy to heat and rub concrete; however, the HRM powder can be used for a soil stabiliser and cement raw material. Life cycle CO_2 and energy of the recycled aggregate are calculated to evaluate this technology. The recycled aggregate is produced from demolished concrete and the HRM powder is used for a soil stabiliser in Case 1-1. The HRM powder is used as a part of cement raw materials in Case 1-2. The production of crashed stone, which is the most popular type of aggregate, is calculated in Case 2. The result of life cycle CO_2 is shown in **Fig. 6**. In Case 1-1

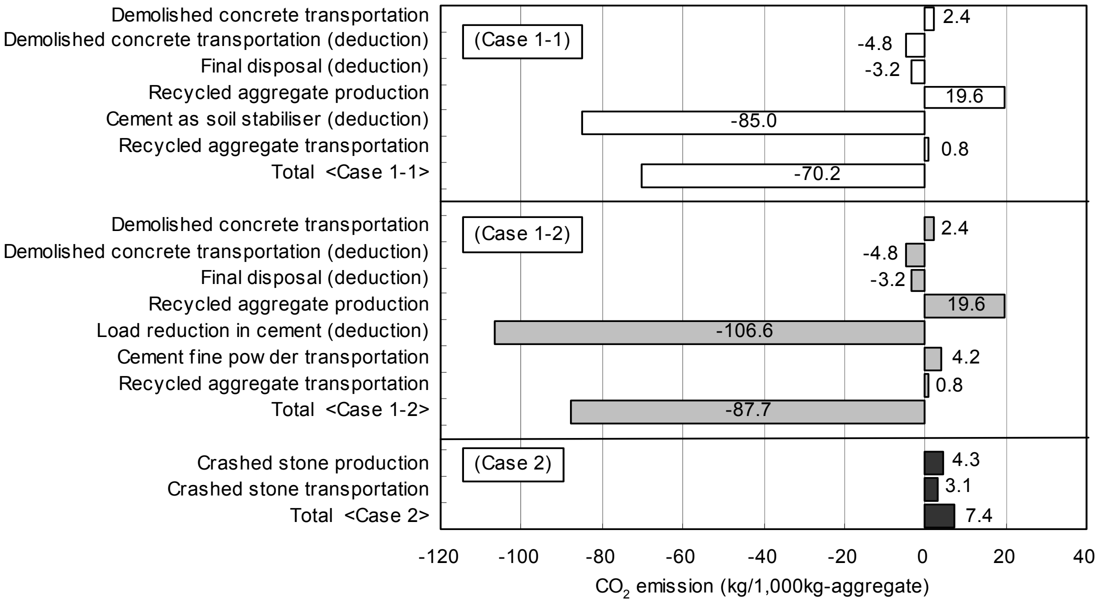


Fig. 6 Life cycle CO_2 of high-quality recycled aggregate by HRM.

and Case 1-2, the life cycle CO_2 is a negative value because the deduction of CO_2 emission during cement manufacturing by the powder is much larger than the emission during recycled aggregate production. In Case 2, the CO_2 emission from crashed stone production is very small but still positive. This method is proved to be very effective to reduce CO_2 in keeping with the Kyoto Protocol. As for the life cycle energy, its use of recycled aggregate is greater than that of crashed stone as ordinary aggregate because the deduction of energy consumption during cement manufacturing by the powder is relatively small (Shima 2003a).

3. Forecasting the generation of demolished concrete

A buildings' lifetime distribution is required to forecast the generation of demolished concrete. This distribution can be determined by fitting the observed remaining rate of buildings to a normal, lognormal, or Weibull distribution (Yashiro 1990). Note that in previous studies, the lifetime of buildings was assumed to be uniformly distributed, and the influence of changes in a building's lifetime and economic parameters was not considered.

In this study, the long-term demolition rate of buildings calculated from fixed asset statistics is investigated and regressed using the proportional hazard model (PHM; Cox 1972) with the economic indices of the demolition year and the durability indices of the construction year serving as covariates. The lifetime distribution of buildings and the generation of concrete are estimated from the regressed demolition rate (Shima 2003b).

3.1 Demolition rate from fixed asset statistics

In this study, fixed asset statistics from 13 cities were used, featuring the floor area of wooden and non-wooden buildings by year of construction (in three-year intervals starting from 1963-1966). From these data, the demolition rates of wooden and non-wooden buildings by city, year of construction, and year of demolition are obtained via

$$\lambda(i,j) = \frac{I_{i,j} - I_{i,j+1}}{I_{i,j}} \tag{1}$$

where $\lambda(i,j)$ is the demolition rate of buildings built in year i and demolished (or observed) in year j, and $I_{i,j}$ is the existing floor area on 1 January in year j of buildings built between 2 January in year i-1 and 1 January in year i+2.

3.2 Regression of the demolition rate using a proportional hazard model

(1) Proportional hazard model (PHM)

The PHM is used for taking into account indices of economic activity and building durability (Eq. 2); it consists of a time-dependent baseline hazard function $\lambda_0(t)$, and an exponential term. A Weibull distribution (often used for predicting a lifetime in the field of reliability engineering) is used as the baseline hazard function (Eq. 3), with the average lifetime T being the time t when this remaining function $R(t)$ is 0.5, which means that the number of remaining building has been halved.

$$\begin{aligned}\lambda(i,j) = \lambda_0(j-i)\exp\big(&\beta_{c1}X_{i,1} + \beta_{c2}X_{i,2} + \cdots + \beta_{cm}X_{i,m} + \\ &+\beta_{d1}X_{j,1} + \beta_{d2}X_{j,2} + \cdots + \beta_{dn}X_{j,n}\big)\end{aligned} \tag{2}$$

$$\lambda_0(t) = m \cdot \frac{\ln(2)}{T^m} \cdot t^{m-1} \tag{3}$$

where $\beta_{c1} \sim \beta_{cm}$, $\beta_{d1} \sim \beta_{dn}$ are the regression parameters of the covariates $X_{i,1} \sim X_{i,m}$, $X_{j,1} \sim X_{j,n}$ at year of construction i and year of demolition j . m is a shape parameter.

(2) Covariates

The economic growth rate (GDP growth rate), official

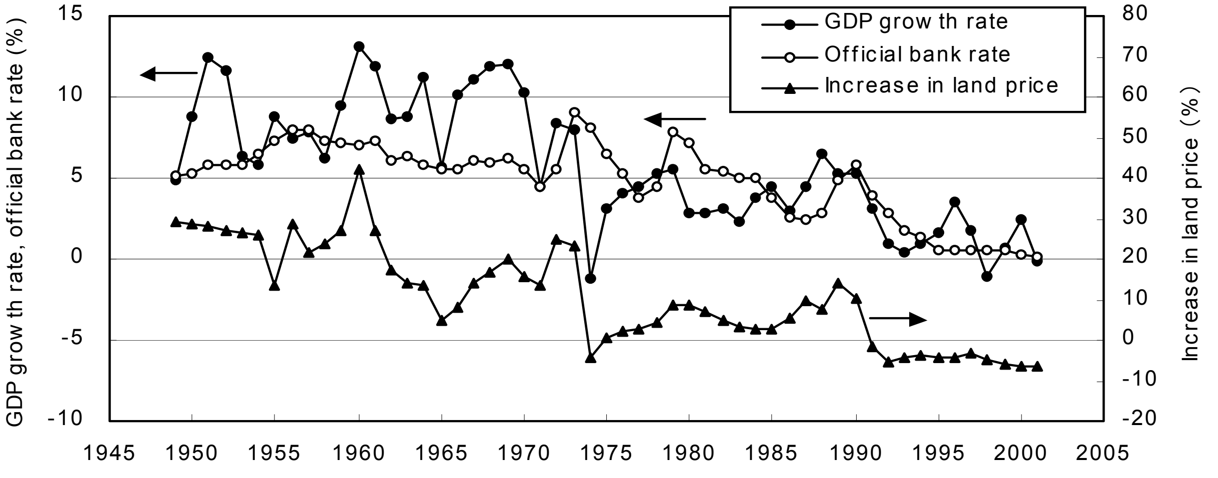


Fig. 7 Changes in covariate as economic indices.

bank rate, and increase in land price are used as the covariates for the year of demolition. Their trends from 1949 onwards are shown in **Fig. 7**. The GDP growth rate in the years prior to or following demolition may have a larger influence than the GDP growth rate in the year of demolition, so these rates are added to the covariates.

In order to analyse the effect of durability of a building over its lifetime, a dummy variable, which is 0 for before 1979 and 1 for after 1980 is used as the covariate for the year of construction. This dummy variable is adopted because of a major amendment to the law dealing with earthquake-resistant architecture.

There is a movement to extend the lifetime of buildings through rehabilitation and interior renewal. This effect can be analysed by setting the numbers or monetary value of the application of such rehabilitation and interior renewal to structures as covariates. However, it might be difficult to obtain the significant coefficients of these covariates since this trend may have started in the 1990s, making the term for the regression too short. Therefore, these covariates were not chosen in this study.

(3) Calculation of regression

The demolition rates obtained from the statistics for each city and the average of all the cities (Eq. 1) were regressed using the PHM (Eq. 2) in order to obtain the parameters of the Weibull distribution as the baseline hazard function, as well as the regression parameters of the covariates. The average demolition rate was obtained as an average over buildings in all cities, weighted according to their floor areas. Significant regression parameters were selected according by employing a t test, applying a significance level of 95%.

(4) Results

The regressed parameters are shown in **Table 1** for the average of all the cities. The average demolition rates, a) obtained from the statistics, and b) estimated using the PHM, are shown in **Figs. 8** and **9**. In **Table 1**, the R^2 values for the coefficients relating to wooden and non-wooden buildings are both above 0.95. Similarly, the t values for m and T in the Weibull distribution are very large, so that applying this formulation for the baseline hazard function is also adequate.

Table 1 Results of regression by PHM.

Structure		Wooden building		Non-wooden building	
Variables		Regression Parameter	t-value	Regression Parameter	t-value
Weibull m		3.02	51.4	3.01	60.1
Weibull T		40.0	102.5	50.7	146.3
GDP growth rate	This year	0.031	3.6	0.040	6.3
Official bank rate	Previous year	0.091	14.0		
	This year			0.083	12.3
Increase in land price	Next year	0.023	8.4		
Dummy (=0 before 1979, =1 after 1980)		-0.357	-3.0		
Coefficient of determination R^2		0.966		0.959	

(a) Average of all the cities

For the covariates in the year of demolition, the GDP growth rate, official bank rate (previous year) and land price increment (next year) are significant for wooden buildings, and so are the GDP growth rate and official bank rate (previous year) for non-wooden buildings. The demolition rate of buildings increases with an in-

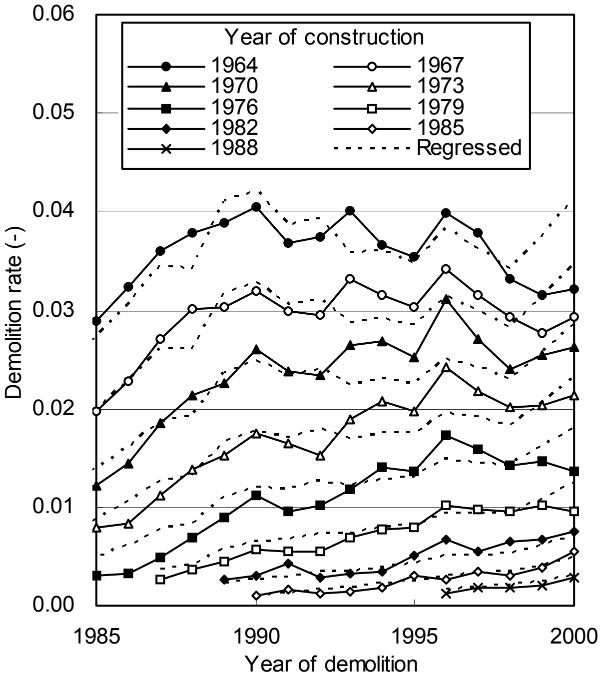


Fig. 8 Regressed demolition rate by PHM for wooden buildings.

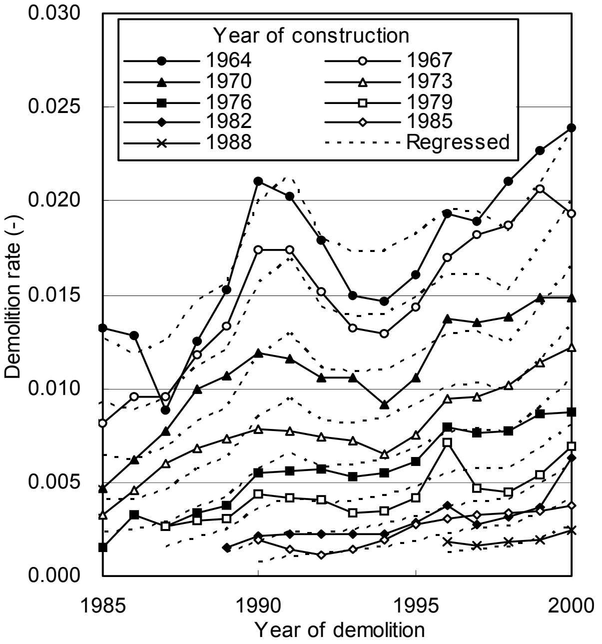


Fig. 9 Regressed demolition rate by PHM for non-wooden buildings.

crease in the covariates because their regression parameters are all positive. For example, the regressed parameter of the GDP growth rate for a non-wooden building is 0.040, meaning that the demolition rate increases by 4% (exp(0.040) = 1.04) for each unit increase of the GDP growth rate.

The dummy variable as a covariate in the year of construction is significant only for wooden buildings, and its estimated value is -0.357. This means that the demolition rate for buildings built after 1980 is a factor of 0.7 (exp(-0.357) = 0.70) lower compared with those built before 1979, and their lifetime is prolonged because of better durability. It is noticeable that this reduction in the demolition rate is not affected by other covariates. As **Figs. 8** and **9** show, unique changes in demolition rate are successfully regressed using the PHM.

(b) Single cities

For wooden buildings, the R^2 values for single cities are very high (0.90 to 0.95), and the GDP growth rate is significant for most of the cities. For non-wooden buildings, the R^2 values are relatively low (0.77 to 0.95), and significant variables do not exist for Tokyo, Chiba, Nagoya, Osaka and Kobe, partly owing to the fact that the period of available statistics is shorter than 10 years.

3.3 Average lifetime of concrete structure

The remaining ratio of the buildings built after 1950 is calculated using Eq. (4), incorporating the demolition rate estimated by the PHM.

$$\begin{aligned} R(i,j) &= R(0.5) \fallingdotseq 1 \qquad (i=j) \\ &= R(0.5)\prod_{k=i+1}^{j}\left(1-\lambda(i,k)\right) = \prod_{k=i+1}^{j}\left(1-\lambda(i,k)\right) \quad (i<j) \end{aligned} \tag{4}$$

Table 2 Predictions of economic indices.

		2001-2010	2011-2020	2021-2030
Increase in investments for construction *1		-1.5	-1.1	0.0
GDP growth rate	High	2.0	2.0	2.0
	Medium *2	1.6	1.5	1.5
	Low	1.0	1.0	1.0
Official Bank Rate	High	0.1	1.5	1.5
	Medium *3	0.1	1.0	1.0
	Low	0.1	0.5	0.5
Increase in land price *4		-3.7	0.0	0.0

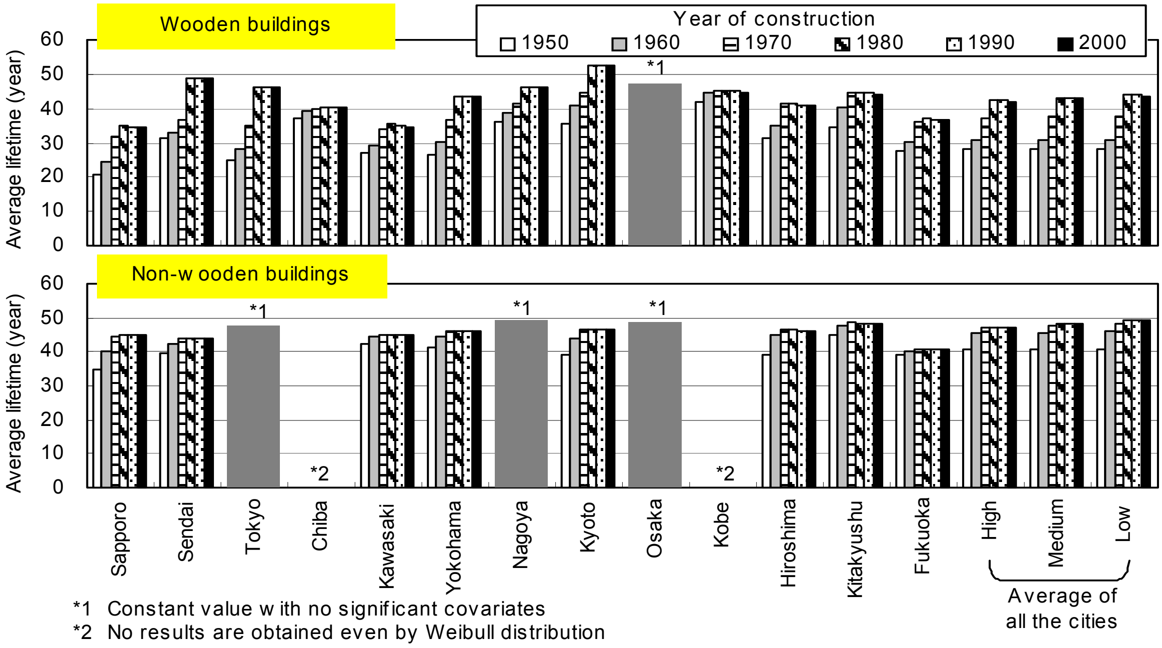
*1 (RICE 2001)
*2 (EDMC 2003, KKRI 2003a, 2003b, Miyagawa 2002, MRI 2003, Suzuki 2004)
*3 (KKRI 2003b, MRI 2003)
*4 (Suzuki 2004)

Here, R(*i,j*) is the remaining ratio at the end of year *j* of buildings built in year *i*. R(*0.5*) is the remaining ratio at the end of year *i* of buildings built in year *i*, which is assumed to be 1. λ(*i,j*) is the demolition rate of buildings built in year *i* and demolished in year *j*.

For buildings built in year *i*, the average lifetime is calculated as *j*-*i*+0.5 using year *j* for which R(*i,j*) is equal to 0.5. The reason why 0.5 is used is because the remaining ratio is calculated at the end of year *j*, but the demolition rate is calculated at the middle of year *j*.

Since the covariates in future demolition years are required for the estimation of the lifetime and generation of demolished concrete, they are given as a scenario in **Table 2** considering predictions by some economic research institute. In the scenario, 'high' and 'low' cases are provided to analyse the variation of covariates.

The average lifetimes for the 'middle' case of buildings in each city and the average of all the cities are shown by decade in **Fig. 10**. For the average of all the cities, lifetimes of wooden and non-wooden buildings



*1 Constant value with no significant covariates
*2 No results are obtained even by Weibull distribution

Fig. 10 Estimated average lifetime of buildings (medium case).

built in 1950 are 28.2 and 40.9 years, respectively. On the other hand, lifetimes of buildings built in 2000 are 42.0 and 48.1 years, longer than those built in 1950. This is because buildings built around 1950 were demolished at a high rate during periods of rapid economic growth. For wooden buildings, the demolition rate is reduced by the improvement of durability after 1980. The lifetimes for the 'high' and 'low' cases are also presented in order to analyse the variation of the predicted economic indices. These variations do not affect to a marked degree increases in lifetimes.

With regard to the differences between cities, for wooden buildings, the average lifetime of the buildings built in 2000 is relatively short (approximately 35 years) for Sapporo and Kawasaki. On the other hand, it is 53 years for Kyoto. Kyoto is Japan's well-known old capital and it has a municipal ordinance to maintain its heritage. This situation may have an influence on the long lifetime of buildings there even though this result is based on buildings built after 1963. For non-wooden buildings, average lifetimes are similar across cities, being 45 to 48 years for buildings built in 2000.

3.4 Generation of demolished concrete

(1) Estimation method

The generation of demolished concrete is estimated by the demolition probability density, obtained by multiplying the demolition rate and the remaining ratio, which are for non-wooden buildings and the average of all the cities. The domestic shipment of concrete for building construction is used for the input of concrete. The input of concrete in the future changes with the predicted increase in investments for construction listed in **Table 2**.

$$W(j) = G \sum_{i=1950}^{j} \left[C_i \cdot R(i, j-1) \cdot \lambda(i, j) \right] \tag{5}$$

Here, W(*j*) is the generation of concrete in year j (*j*>1950)(ton), *G* is the generation-to-input ratio of concrete, assumed to be 0.8 (-), R(*i,j*) is the remaining ratio, λ(*i,j*) the demolition rate, and C_i the shipment of the concrete for building construction in year *i* (ton).

(2) Results

The estimated generation of concrete is shown in **Fig. 11** for three cases. There was a peak in 1991, a year in which economic indices were high and the generation of concrete reached 29 million tons. After the 1991 peak, there was a small reduction, with the 1991 level was reached again only in 1998. The dip in concrete generation after 1991 was caused by low covariates and reflects a severe recession. After that, the generation of concrete grew rapidly and reached 60 and 100 million tons in the middle case by 2010 and 2023, respectively. This real situation in which the generation of concrete is hampered by the recession can be expressed by our model. The difference in the generation of demolished concrete between the cases is fairly limited, and the generation of concrete is currently increasing drastically in all cases.

4. Generalised input-output table for accommodating concrete-related industries

4.1 Input-output analysis

Input-output analysis is one of the tools of economics that is widely used to analyse the repercussion of an economic activity (UN 1999). In an input-output table, the exchange of products among industries is described in monetary terms. Input-output tables are published by the Japanese government every five years. In order to analyse the repercussions of final demand, the input coefficient matrix A is defined as shown below. The (*i,j*) entry of A - a_{ij} - is the amount of product i in monetary value needed for producing one value unit of product *j* . **g** is the vector of total product output, and the *j* entry of **g**, g_j, is the amount of total output of product *j*. **F** is assumed to be the vector of final demand of products . Equation 6 is obtained by balancing inputs and outputs. The items and numbers of industries in rows and col-

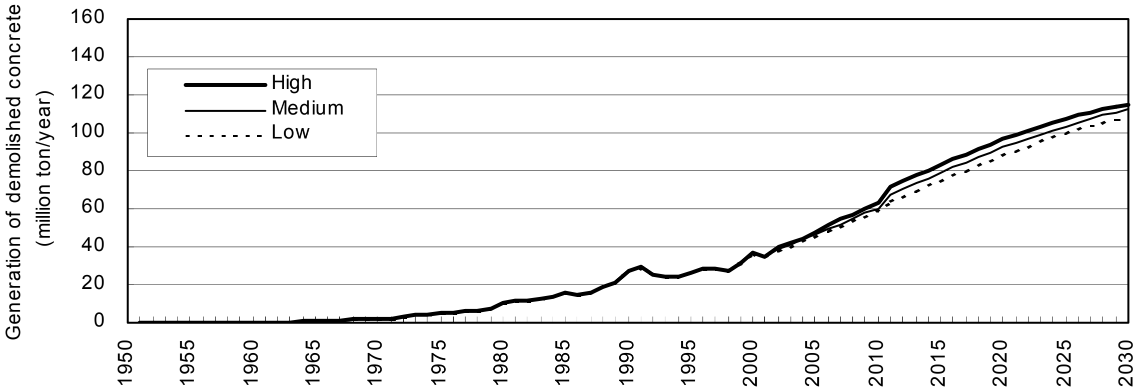


Fig. 11 Estimated generation of demolished concrete from building construction field.

umns are set to be the same by appropriate classification, so that input coefficient matrix is symmetric. An inverse matrix is obtained via Eq. (7)

$$\mathbf{g} = \mathrm{A}\mathbf{g} + \mathbf{F} \tag{6}$$

$$\mathbf{g} = (\mathrm{I} + \mathrm{A} + \mathrm{A}^2 + \mathrm{A}^3 + \mathrm{L} + \mathrm{A}^n + \mathrm{L})\mathbf{F} = (\mathrm{I} - \mathrm{A})^{-1}\mathbf{F} \tag{7}$$

$(\mathrm{I}\text{-}\mathrm{A})^{-1}$ is a so called Leontief inverse. Using this matrix, **g** is obtained from the vector of final demand. This means the repercussions of final demand can be analysed.

In this type of analysis, however, byproducts and environmental emissions, e.g., CO_2 and waste, cannot be handled because it is assumed that one industry produces only one product. In this study, therefore, a process-related model (Yoshioka 1998, Matsuhashi 2000) is used to include them. Output coefficient matrix E is defined as follows: The (i,j) entry of E - e_{ij} (i≠j) - is the amount of byproduct i when producing one value unit of main product from process j. e_{ii}, which is the output coefficient of main product i from process i, obviously equals 1. In this model, the items and numbers of product and process are not necessarily the same. The unit of i entry of the vector of total product output **q** and j entry of the vector of main product output **g** is arbitrary and can be a monetary value or a physical value, e.g., ton and cubic meter. Equation (8) is obtained by taking the balance of supply and demand of products and by defining E-A as B

$$\mathrm{B}\mathbf{g} = \mathbf{F} \tag{8}$$

where **g** is the vector of main product output, and the j entry of **g**, g_j, is the amount of main product output from process j. **F** is the vector of final demand of products.

4.2 Framework of extended input-output table

The input-output table published by the Japanese government in 1995 is extended by the detailed description of concrete-related industries and the addition of several concrete recycling processes including the HRM. The framework of the extended input-output coefficient matrix is shown in **Fig. 12**. The partial matrices are explained below.

(1) Matrix B_{11} corresponds to the difference of matrix E_{11}(output coefficient matrix) and A_{11}(input coefficient matrix) of conventional industrial processes. E_{11} describes the output of the main products from these processes. The concrete-related industries, e.g., building construction, aggregate, clinker, cement, ready-mixed concrete are disaggregated by raw material and usage. (2) B_{12} is also equivalent to E_{12}-A_{12}. These are the output and input coefficient matrix for the concrete-related recycling processes, respectively. For example, when the HRM is operated, aggregate is the main recycled product described in E_{12} and electricity consumed in HRM is one of the needed products described in A_{12}. (3) B_{21} as E_{21}-A_{21}, E_{21} is for the output coefficient of the waste and byproducts for producing one unit value of the conventional industrial products. When the waste and byproducts, e.g., fly ash and blast furnace slag, are used as raw materials for the cement process, these are described in A_{21}. (4) B_{22} as E_{22}-A_{22}, A_{22} is the input coefficient matrix of the waste and byproducts treated in the recycling processes. (5) In B_{31} and B_{32}, CO_2 emission and final disposal for producing one unit value of conventional industrial products and recycled products as in E_{31} and E_{32}. $\mathbf{v}_1$ is the vector of value added rate of conventional industrial processes and provided from the input-output table in 1995. $\mathbf{v}_2$ is also the value added rate for the recycling processes and is estimated from labor, tax, and facility depreciation, etc.

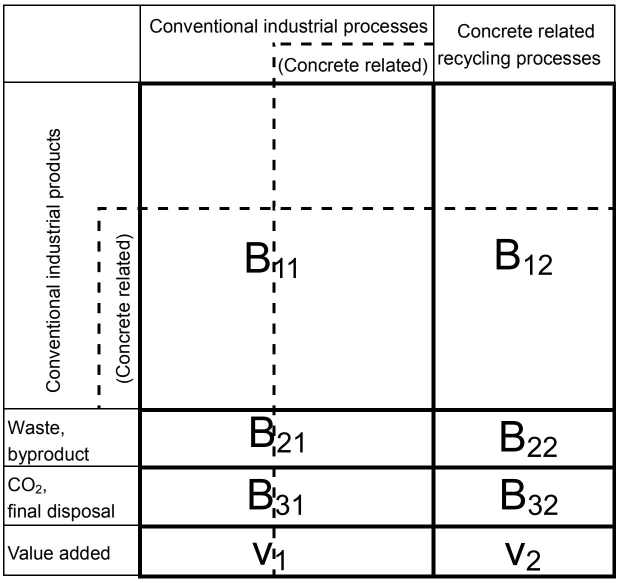


Fig. 12 Framework of extended input-output table.

4.3 Processes and products and in the extended input-output table

The processes in the extended input-output table are listed in **Table 3** and **Table 4**. No. 1 to 29 are the conventional industries taken from the published Japanese input-output table (519 rows, 403 columns). No. 30 to 52 are the concrete-related processes of the conventional industries. No. 53 to 81 are the recycling processes.

Building construction, road and civil engineering (No. 30 to 37, 53 to 56) are divided into three kinds of ready-mixed concrete: (1) ready-mixed concrete with ordinary portland cement (OPC); (2) ready-mixed concrete with blast furnace slag cement (BFSC), fly ash cement (FAC), or HRM powder cement; and (3) ready-mixed concrete with low-quality (LQ) recycled aggregate. Regarding (2), BFSC is popular in civil engineering because its environmental load is low, but it is not as commonly used as OPC in building construction in Japan because it delays the demolding of concrete with a resulting cost increase. (3) is limited to uses in low strength concrete or non-structural construction, etc.

Road (No. 32 to 35 and 54, 55) is divided according to the method of construction into (1) and (2). (1) corresponds to new road construction or complete replacement of road subbase. (2) represents cutting overlay, in which only the surface asphalt layer is changed.

A cement manufacturing process is divided into several cement and clinker manufacturing processes. The clinker manufacturing process is also divided into five types of processes according to the raw materials. Only natural raw materials, e.g., limestone, silica stone, and clay are used for No. 42. For other clinkers, No. 43, 44, 57, 81, the raw materials of each process are composed of one particular material, e.g., BFS, FA and HRM powder and other natural materials, in order to be able to express the difference of environmental load for each clinker manufacturing process.

Several cement processes are provided. No. 60 is OPC containing 5% HRM powder, and No. 62 is BFSC containing 10% HRM powder. A soil stabiliser (No. 61) is made to add the 67% HRM powder to the cement soil stabiliser (No. 48). The mixed cements, e.g., BFS and FA cement (No. 46, 47), OPC containing 5% admixture (No. 58, 59) are also added to the processes.

In the area of concrete recycling technology, the mechanical grinding method (MGM) was also developed. MGM uses a vertical cylinder with an eccentric rotor inside. Demolished concrete is rubbed between the cylinder and rotor to obtain 30% of high-quality recycled aggregate and 70% of road subbase. Five concrete recycling or treatment processes are provided: (a) HRM (No. 70), (b) MGM (No. 71), (c) low-quality recycled aggregate production that produces 100% of the aggregate by simple crushing and classifying (No. 72), (d) road subbase production (No. 73), and (e) final disposal (least controlled) (No. 74).

The conventional industrial products, waste and by-products, final disposal and CO_2 emission, and value added are listed in **Table 5**. The products produced by several processes are united into one product when these products are considered to have the same function. For example, the ready-mixed concrete with OPC and gravel (process number 49) and ready-mixed concrete with OPC and crashed stone (for concrete) (process number 51) are united into the ready-mixed concrete with OPC (product number 44) as a product.

4.4 Results

Table 5 shows the extracted output coefficient matrix B as shown in **Fig. 12** for some characteristic processes. The process numbers correspond to those shown in **Table 3** and **Table 4**. As explained in section 4.1 and 4.2, the values for each process correspond to the output amounts for one unit of main product or treated waste. The unit of the output is indicated in the last column and

Table 3 Conventional industrial processes including concrete-related processes.

No.	Process	No.	Process
Conventional industrial process		Concrete related conventional industrial process	
1	Agriculture and fishery	(Building construction)	
2	Mining	30	with ready-mixed concrete (OPC)
3	Limestone mining	31	with ready-mixed concrete (BFS, FA, HRM Powder)
4	Ceramic raw materials	(Road)	
5	Coal	32	with ready-mixed concrete (OPC)
6	Crude oil	33	with ready-mixed concrete (BFS, FA, HRM Powder)
7	Natural gas	34	Cutting and overlay method with ready-mixed concrete (OPC)
8	Food etc	35	Cutting and overlay method with ready-mixed concrete (BFS, FA, HRM Powder)
9	Chemical products	(Civil engineering)	
10	Oil products	36	with ready-mixed concrete (OPC)
11	Coal products	37	with ready-mixed concrete (BFS, FA, Powder)
12	Pavement materials	(Aggregate)	
13	Miscellaneous ceramics and rocks	38	Gravel
14	Cement products	39	Crushed stone (high quality for concrete)
15	Steel	40	Crushed stone (for upper road subbase)
16	Nonferrous metals	41	Crushed stone (for lower road subbase)
17	Metal products	(Cement clinker)	
18	Machinery	42	Natural raw materials
19	Industrial goods	43	BFS and natural raw materials
20	Electricity	44	FA and natural raw materials
21	City gas	(Cement)	
22	Heat supply	45	OPC (containing 2% BFS)
23	Water supply and industry water	46	BFS cement (OPC containing 40% BFS)
24	Sewage	47	FA cement (OPC containing 40% FA)
25	Waste treatment	48	Cement soil stabilizer
26	Trade	(Ready-mixed concrete)	
27	Transportation	49	OPC and gravel
28	Road freight transportation	50	BFS cement and gravel
29	Costal freight transportation	51	OPC and crushed stone (for concrete)
		52	Ready-mixed concrete (BFS cement and gravel)

Table 4 Concrete-related recycling processes.

No.	Concrete-related recycling process
(Construction)	
53	Building construction with ready-mixed concrete (LQ recycled aggregate)
54	Road with ready-mixed concrete (LQ recycled aggregate)
55	Road (cutting and overlay method) with ready-mixed concrete (LQ recycled aggregate)
56	Civil engineering with ready-mixed concrete (LQ recycled aggregate)
(Clinker and cement)	
57	Clinker (HRM powder and natural raw material)
58	OPC（containing 5% BFS)
59	OPC（containing 5% FA）
60	OPC (containing 5% HRM powder)
61	Soil stabilizer (containing 67% HRM powder)
62	HRM powder cement（BFS cement containing 10% HRM powder）
(Ready-mixed concrete)	
63	FA cement and gravel
64	HRM powder cement and gravel
65	FAC and crushed stone (HQ)
66	PC and crushed stone (HQ)
67	BFS Cement and LQ recycled aggregate
68	FA Cement and LQ recycled aggregate
69	HRM powder cement and LQ recycled aggregate
(Treatment and disposal of demolished concrete)	
70	HQ recycled aggregate production by HRM
71	HQ aggregate production by MGM
72	LQ recycled aggregate production
73	Road subbase production
74	Final disposal (least controlled)
(Other)	
75	BFS treatment by road subbdase
76	BFS final disposal (least controlled)
77	Coal ash for civil engineering use
78	Coal ash final disposal (least controlled)
79	HRM powder for road subbase admixture
80	Industrial waste final disposal (controlled)
81	Industrial waste cement clinker raw material

that of the main product or treated waste is indicated in the last row. Negative values correspond to inputs in this table. For example, in the case of HRM powder cement (process number 62), 75 yen of ceramic raw material (gypsum), 521 kg of cement clinker, 360 kg of BFS, and 100 kg of HRM powder are needed as raw materials to produce one ton of cement is produced. One hundred and eighty four yen of electricity (for grinding BFS) and 600 and 180 yen of road and costal freight transportation, respectively (for BFS and HRM powder transportation), are also needed. The transportation cost is calculated from the average transportation distance and the transportation cost per distance.

The CO_2 emission of each process corresponds to CO_2 from the combustion of fuel and raw material like limestone. However, it does not include CO_2 from electricity, transportation, and fuel manufacturing and transportation, etc., because its indirect CO_2 is bound to be calculated considering the repercussions and added to the total CO_2 emission. For example, in the case of HRM powder cement, CO_2 emission from the transportation of BFS and HRM powder is calculated in the processes of transportation (process numbers 28 and 29 in **Table 3**) brought by the repercussions.

5. Scenario modeling of a future concrete recycling system using an optimisation model

5.1 Structure of optimisation model

Solutions are optimised for the years 2010, 2020 and 2030 for a given predicted final demand from each industry and predicted generation of demolished concrete. Our optimisation model is a semi-dynamic model in which the increasing amount of a recycling process in a decade is limited to a certain level.

(1) The input coefficient matrix based on the published 1995 input-output table is used for every year, assuming that the production recipes for cement and concrete related industries have almost matured and will not changed very much in the future. Fundamentally, an input-output table should be updated for the future years. The RAS method is used for estimating a future table by examining the changes in the coefficients of two tables in different years (UN 1999). However, estimating future coefficients from changes in past tables is not necessarily successful and does not assure an improvement in the accuracy of the model. Therefore, a constant production recipe is used in this study.

(2) Optimisation of the model is carried out by minimizing the total value added (cost) under the condition that the balance of supply and demand is satisfied, and the usage ratio of recycled products is limited as described in section 5.2.

(3) The final demand of each product except that of the construction industries is changed with the GDP growth rate predicted by some research institutions listed in **Table 2** (1.6% from 2001 to 2010 and 1.5% from 2011 to 2030). The future increase in investment is predicted to be a negative value for construction industries. This final demand is changed with the predicted ratios also listed in **Table 2** (-1.5% from 2001 to 2010, -1.1% from 2011 to 2020, and 0% from 2021 to 2030).

5.2 Solving the model

B_1 is composed of the partial matrixes B_{11} and B_{12} shown in **Fig. 12** as well as B_2 and B_3. $\mathbf{g}$ is the vector of product output produced by the industrial and recycling processes. $\mathbf{F}$ is the vector of final demand. $\mathbf{v}$, composed of $\mathbf{v}_1$ and $\mathbf{v}_2$, is the vector of the value added rate. $\mathbf{r}$ is the vector of the upper limit of environmental emission load.

$$B_1\mathbf{g} \geq \mathbf{F} \tag{9}$$

$$B_2\mathbf{g} = \mathbf{0} \tag{10}$$

$$B_3\mathbf{g} \leq \mathbf{r} \tag{11}$$

$$\mathbf{vg} \rightarrow \min \tag{12}$$

Table 5 Output coefficient matrix B (extracted).

		Process (column) Product (row)	30	33	35	39	42	43	45	46	51	52	62	67	69	70	71	72	73	74	Unit
			Conventional industrial process (concrete related)										Concrete-related recycling process								
			Building construction with ready-mixed concrete (OPC)	Road with ready-mixed concrete (BFS, FA, HRM Powder)	Road (Cutting and overlay method) with ready-mixed concrete (BFS, FA, HRM Powder)	Crushed stone (high quality for concrete)	Clinker (Natural raw materials)	Clinker (BFS and natural raw materials)	OPC (containing 2% BFS)	BFS cement (OPC containing 40% BFS)	Ready-mixed concrete (OPC and crushed stone (for concrete))	Ready-mixed concrete (BFS cement and crushed stone (for concrete))	HRM powder cement (BFS cement containing 10% HRM powder)	Ready-mixed concrete (BFS cement and LQ recycled aggregate)	Ready-mixed concrete (HRM powder cement and LQ recycled aggregate)	Treatment and disposal of demolished concrete (HQ recycled aggregate production by HRM)	Treatment and disposal of demolished concrete (HQ aggregate production by MGM)	Treatment and disposal of demolished concrete (LQ recycled aggregate production)	Treatment and disposal of demolished concrete (Road subbase production)	Treatment and disposal of demolished concrete (Final disposal (least controlled))	Unit
1	Conventional industrial product	Agriculture and fishery	-1	-3	-3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	yen
2		Mining	0	0	0	0	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	
3		Limestone mining	0	0	0	0	-896	-735	0	0	-3	-3	0	-3	-3	0	0	0	0	0	
4		Ceramic raw materials	0	0	0	0	-84	-84	-136	-83	-3	-3	-75	-3	-3	0	0	0	0	0	
5		Coal	0	0	0	0	-631	-544	0	0	0	0	0	0	0	0	0	0	0	0	
6		Crude oil	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
7		Natural gas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
8		Food etc	-94	-10	-10	-11	-251	-251	0	0	-17	-17	0	-17	-17	0	0	0	0	0	
9		Chemical products	-7	-2	-2	-10	-5	-5	0	0	-43	-43	0	-43	-43	0	0	0	0	0	
10		Oil products	-1	-7	-7	-5	-26	-26	0	0	-27	-27	0	-27	-27	-236	-15	-15	-15	-8	
11		Coal products	0	0	0	0	-2	-2	0	0	0	0	0	0	0	0	0	0	0	0	
12		Pavement materials	0	-26	-26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
13		Miscellaneous ceramics and rocks	-23	-7	-7	0	-143	-143	0	0	-53	-53	0	-53	-53	0	0	0	0	0	
14		Cement products	-11	-36	-36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
15		Steel	-16	-16	-16	0	-12	-12	0	0	0	0	0	0	0	0	0	0	0	0	
16		Nonferrous metals	-3	-5	-5	0	-4	-4	0	0	0	0	0	0	0	0	0	0	0	0	
17		Metal products	-116	-71	-71	-26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
18		Machinery	-21	-4	-4	-4	-33	-33	0	0	0	0	0	0	0	0	0	0	0	0	
19		Industrial goods	-16	-23	-23	-12	-105	-105	0	0	-38	-38	0	-38	-38	0	0	0	0	0	
20		Electricity	-4	-5	-5	-21	-565	-565	-350	-540	-71	-71	-184	-71	-71	-609	-187	-63	-63	0	
21		City gas	-1	0	0	0	0	0	0	0	-2	-2	0	-2	-2	0	0	0	0	0	
22		Heat supply	0	0	0	0	-1	-1	0	0	0	1	0	0	0	0	0	0	0	0	
23		Water supply and industry water	-1	0	0	-3	-17	-17	0	0	-20	-20	0	-20	-20	0	0	0	0	0	
24		Sewage	0	0	0	-1	-4	-4	0	0	-6	-6	0	-6	-6	0	0	0	0	0	
25		Waste treatment	0	-1	-1	-2	-2	-2	0	0	-35	-35	0	-35	-35	0	0	0	0	0	
26		Trade	-158	-191	-191	-141	-1,333	-1,333	0	0	-1,457	-1,457	0	-1,457	-1,457	0	0	0	0	0	
27		Transportation	-29	-34	-34	-317	-127	-441	-20	-435	-1,039	-1,039	0	-1,039	-1,039	0	0	0	0	0	
28		Road freight transportation	-22	-26	-26	-4	-69	-240	-11	-237	-1,007	-1,007	-600	-1,007	-1,007	-1,000	-1,000	-1,000	-1,000	-2,500	
29		Costal freight transportation	-1	-2	-2	0	-8	-28	-1	-28	-181	-181	-180	-181	-181	0	0	0	0	0	
30	(concrete related)	Building construction	999	-2	-2	-3	-80	-80	0	0	-10	-10	0	-10	-10	0	0	0	0	0	yen
31		Road	0	1,000	1,000	-1	-19	-19	0	0	-2	-2	0	-2	-2	0	0	0	0	0	
32		Civil engineering	0	-1	-1	-2	-53	-53	0	0	-6	-6	0	-6	-6	0	0	0	0	0	
33		Gravel	-0.43	-3.21	-3.21	0	-5	-5	0	0	-624	-624	0	-624	-624	650	0	0	0	0	kg
34		Crushed stone (high quality for concrete)	-0.07	-0.13	-0.13	1,000	0	0	0	0	-1,213	-1,213	0	0	0	0	300	0	0	0	
35		(low quality for concrete)	0	0	0	0	0	0	0	0	0	0	0	-1,213	-1,213	0	0	1,000	0	0	
36		(for upper road subbase)	-0.57	-9.69	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
37		(for lower road subbase)	0	-9.69	0	0	-8	-8	0	0	0	0	0	0	0	0	700	0	1,000	0	
38		Cement clinker	0	0	0	0	1,000	1,000	-946	-579	0	0	-521	0	0	0	0	0	0	0	
39		OPC	-0.03	0	0	0	-5	-5	1,000	0	-280	0	0	0	0	0	0	0	0	0	
40		BFS cement	0	-0.05	-0.05	0	-1	-1	0	1,000	0	-296	0	-296	0	0	0	0	0	0	
41		FA cement	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
42		Cement soil stabilizer	-0.05	-0.05	-0.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
43		HRM powder cement	0	0	0	0	0	0	0	0	0	0	1,000	0	-296	0	0	0	0	0	
44		Ready-mixed concrete (OPC)	-1.25	0	0	0	0	0	0	0	1,000	0	0	0	0	0	0	0	0	0	L
45		(BFSC, FAC, HRM powder cement)	0	-3.00	-3.00	0	0	0	0	0	0	1,000	0	0	0	0	0	0	0	0	
46		(LQ recycled aggregate)	0	0	0	0	0	0	0	0	0	0	0	1,000	1,000	0	0	0	0	0	
47	Waste, byproduct	Blast furnace slag	0	0	0	0	0	-289	-19	-400	0	0	-360	0	0	0	0	0	0	0	kg
48		Fly ash	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
49		Demolished concrete	0	0	0	0	0	0	0	0	0	0	0	0	0	-1,000	-1,000	-1,000	-1,000	-1,000	
50		HRM powder	0	0	0	0	0	0	0	0	0	0	-100	0	0	350	0	0	0	0	
51		Industrial waste	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
52	Final disposal		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1,000	kg
53	CO_2 emission		0.10	0.37	0.37	0.52	868.6	723.7	0	0	3.9	3.9	0	3.9	3.9	28.6	0.79	0.79	0.79	0.42	
54	Value added		458	464	464	579	2,827	2,827	0	0	3,840	3,840	0	3,840	3,840	1,520	1,126	747	637	10,895	yen
Unit			10^3 yen			ton					m^3		ton	m^3		ton					

Equation (9) is obtained because supply is larger than demand. Equation (10) means that waste and byproducts must be treated without any surplus and shortage. The environmental emission load and other constraints are expressed in Eq. (11). Equation (12) corresponds to the minimisation of the total cost. These equations can be solved by linear programming, yielding the vector of product output produced by processes **g**.

As an example of the constraints described in Eq. (11), the upper ratio of cutting overlay, (which doesn't use road subbase) in road construction is shown in Eq. (13). g_{32} and g_{34} are the product output produced by road construction using the conventional method (No. 32 in **Table 3**) and the cutting overlay method (No. 34 in **Table**

3), respectively. In this example, the upper ratio of cutting overlay method is set to 80% in Eq. (13)

$$\frac{\mathbf{g}_{32}}{\mathbf{g}_{32}+\mathbf{g}_{34}}\times 100 \le 80 \tag{13}$$

$$-0.7\mathbf{g}_{32}+0.8\mathbf{g}_{34} \le 0 \tag{14}$$

From Eq. (14) obtained from Eq. (13), b_{i32}=-0.7 and b_{i34}=0.8 are provided in B_3, and r_i=0 is also provided in the vector **r** for this constraint i. By changing these variables, the influence of spread of cutting overlay method can be analysed. For our basic scenario, the limits of the main constraints are shown in **Table 6**. The upper ratios of the ready-mixed concrete with mixed cement, e.g., BFSC, FAC and HRM powder cement and that of low-quality recycled aggregate used for building construction, road construction and civil engineering are estimated to increase by 70 to 90%, and by 5 to 10% in 2030, respectively. The ratio for the cutting overlay method is estimated to increase by 80% in 2030.

The generation of demolished concrete from building construction is estimated using the PHM explained in Chapter 3. The 'middle' case of economic indices shown in **Table 6** is used in this basic scenario. The generation of demolished concrete from civil engineering activities is predicted by the simple Weibull distribution with an average lifetime of 60 years. These estimated values are also listed in **Table 6**. The effect of a carbon tax and subsidy paid for high-quality recycled aggregate is examined by adding them to the added values in the extended input-output table.

5.3 Results and discussion

(1) Basic scenario

The breakdown of the treatment of demolished concrete in the basic scenario is shown in **Fig. 13**. The sum represented by each bar corresponds to the generation of demolished concrete, reaching 200 million tons a year in 2030. The road subbase is the main treatment of the concrete in every year. The HRM is introduced in 2020, and its contribution is 2.5 million tons a year. In 2030, the HRM and mechanical grinding method (MGM) contribute 17 and 60 million tons a year, respectively. The reason for the introduction of the HRM and MGM is their ability to avoid the final disposal of the demolished concrete when its amount exceeds the demand for road subbase, especially when the latter decreases with increasing cutting overlay usage in road construction.

The breakdown of the ready-mixed concrete production is shown in Fig. 14. Concrete with LQ-recycled aggregate begins to be produced, and concrete with BFSC increases due to increased demand in construction, as given in the scenario in 2010. Concrete with HRM powder cement begins to be produced with the introduction of the HRM in 2020. In 2030, all production of concrete with BFSC has shifted to that with HRM powder cement. HRM powder is mainly used for HRM powder cement, but not for cement raw material, when cost are minimised. This indicates that the operation of the HRM method reaches a maximum and the utilization of the powder is the key to increasing use of the HRM.

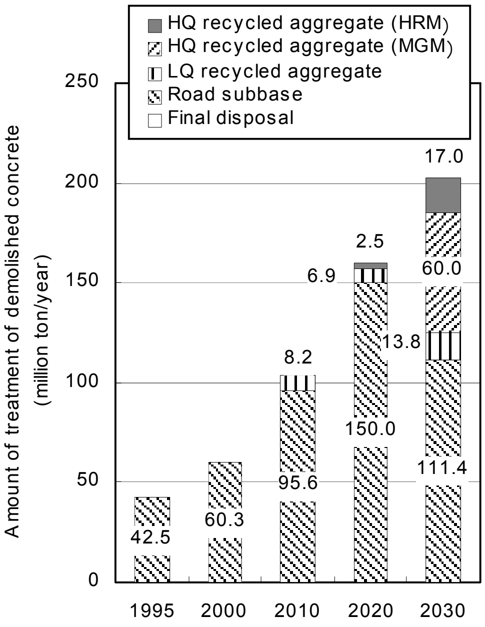


Fig. 13 Breakdown of treatment of demolished concrete.

Table 6 Basic scenario of main waste generation and various constraints.

		Unit	1995	2000	2010	2020	2030	
(Waste generation)								
Fly ash		million ton /year	7.1	8.4	15.0	15.0	15.0	by FA association
Demolished concrete	Building construction		26	37	60	92	112	by PHM
	Civil engineering		16	24	43	67	90	by Weibull distribution
	Total		42	61	103	159	202	
(Constraints)								
Ratio of ready-mixed concrete with mixed cement	Building construction	%	6	7	≦30	≦70	≦70	Values in 1995-2000 are estimated. Values in 2010-2030 are given as scenario.
	Road construction		25	30	≦50	≦90	≦90	
	Civil engineering		25	30	≦50	≦90	≦90	
Ratio of ready-mixed concrete with LQ recycled aggregate	Building construction	%	0	0	≦5	≦5	≦5	
	Road construction		0	0	≦5	≦10	≦10	
	Civil engineering		0	0	≦5	≦10	≦10	
Ratio of cutting overlay method	Road construction	%	16	16	≦37	≦59	≦80	

(2) Influence of a carbon tax

Next, the influence of a carbon tax is analysed. At rates of 2,500 and 1,500 yen/ton-CO_2 in 2010 and 2020, respectively, the contribution of the HRM is increased from 0 to 4 million tons and from 2.5 to 7 million tons in 2010 and 2020, respectively, as shown in **Fig. 15**. If the rates are lower than those shown above, no effect is observed. Since the MGM does not reduce CO_2 emissions, its contribution is not increased by the tax. Thus, the carbon tax accelerates the introduction of the HRM.

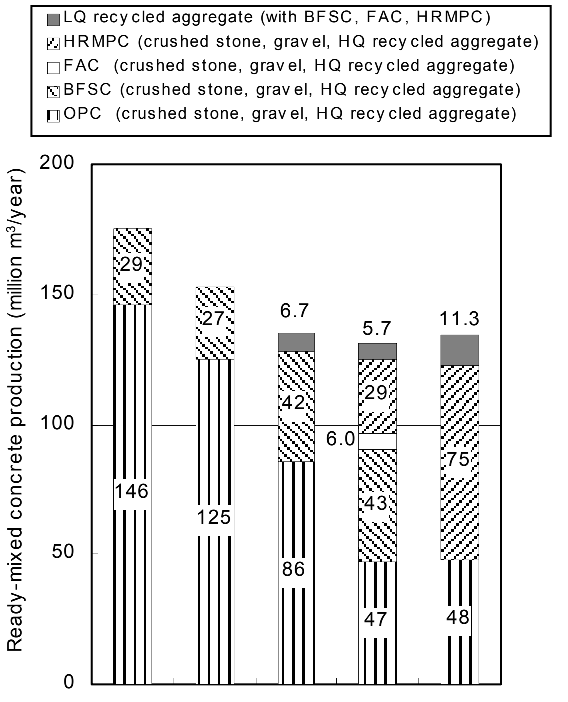


Fig. 14 Breakdown of ready-mixed concrete production.

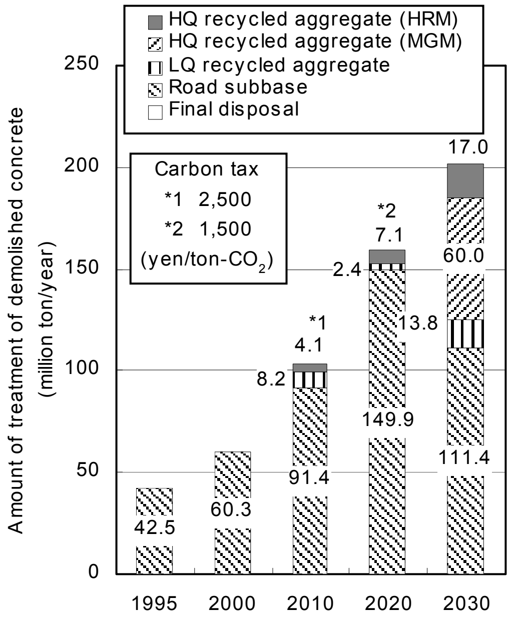


Fig. 15 Breakdown of treatment of demolished concrete with carbon tax.

(3) Influence of a subsidy

The breakdown of contributions is shown in **Fig. 16**, when the subsidy for high-quality recycled aggregate production is set to 750 yen/ton-concrete. The contribution of the HRM is increased from 0 to 4 million tons and from 2.5 to 7 million tons in 2010 and 2020, respectively. The MGM is introduced from 2010, and its contribution increases from 60 to 135 million tons in 2030. The subsidy has no effect, and can be stopped in 2030. Thus, a subsidy at a reasonable rate is very effective for the introduction of both the HRM and MGM.

(4) Influence of spread of cutting overlay method in road construction

Many parametric studies have been carried out to analyse the influence of the variation of spread ratio of mixed cement, low-quality aggregate, FA as cement admixture, etc. In this paper, the case in which the cutting overlay method does not become popular in road construction is analysed. Assuming that the upper ratio of the cutting overlay is kept at 16% (estimated value in 1995), neither HRM nor MGM are introduced, even by 2030. This is because the conventional method in road construction requires a lot of road subbase and the demolished concrete can still be used for road subbase. Even in this case, the subsidy explained above is effective at the same price. With a subsidy of 750 yen/ton-concrete, the extent of use of the HRM and MGM is almost same, as shown in **Fig. 16**.

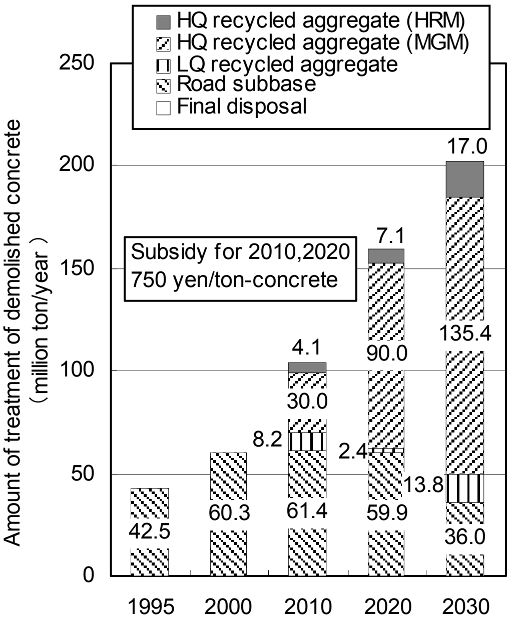


Fig. 16 Breakdown of treatment of demolished concrete with subsidy.

6. Conclusion

To promote the recycling of concrete, a technology to produce high-quality recycled aggregate by the heating and rubbing method has been developed. In this paper, after a description of this technology, a future scenario of concrete recycling system is analysed in order to assess the applicability of the technology using an optimisation model. The model is connected to an input-output table that has been extended by a detailed description of concrete-related industries as well as some concrete recycling processes. For this scenario, a specific model considering indices of economic activity is established to estimate the amount of demolished concrete in the future. The following conclusions are drawn:

(1) The demolition rate of buildings can be regressed using a proportional hazard model with covariates such as the GDP growth rate and official bank rate. The average lifetime of non-wooden buildings built in later years is longer at approximately 48 years than that of buildings built in 1950, for the average of 13 cities in Japan.

(2) The generation of demolished concrete is estimated using the lifetime distribution of non-wooden buildings. After a peak in 1991, there was a small reduction reflecting a severe recession. After that, the generation of demolished concrete has been and will continue growing rapidly, reaching 60 and 100 million tons by 2010 and 2023, respectively.

(3) This model can be widely used for forecasting the lifetime of buildings and the generation of waste from their demolition in other countries by choosing the proper covariates.

(4) Under the estimated generation of demolished concrete, concrete recycling using the heating and rubbing method (HRM) is introduced in 2020. The amount of the treatment by the HRM is increased to 17 million tons a year in 2030, when the the generation of demolished concrete reaches 200 million ton. In order to increase the amount of HRM treatment, the HRM powder generated at the aggregate recovery must be used more efficiently as a cement admixture or otherwise.

(5) A carbon tax of 2,000 to 3,000yen/ton-CO_2 would accelerate the introduction of the HRM because it would reduce CO_2 emission throuth the use of the HRM powder as a cement admixture.

(6) A subsidy for the production of high-quality recycled aggregate is very effective for the introduction of both the HRM and the mechanical grinding method.

(7) This input-output analysis can be used for investigating a proper recycling system focusing on cement and concrete industry as well as the applicability of each individual concrete recycling technology.

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