

ENVIRONMENTAL LOADS OF PAVEMENT RECYCLING METHODS IN JAPAN

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ABSTRACT

In Japan, reclaimed asphalt pavement (RAP) has been used, and the recycling rate of those is now 99%. It means that the asphalt pavement is an effective recycling material. However, the effectiveness of recycling in terms of various environmental load matters such as CO₂ emissions, energy consumptions, SO_x emissions, etc, remains unclear. The total environmental load though the lifecycle is including material production, transportation, paving work, and waste disposal is not known.

In this study, the environmental loads of pavement recycling methods were estimated for three cases using virgin aggregates, plant recycling aggregates, or in-place recycling. The results showed that the environmental loads when using recycled aggregates were less than when using virgin materials, and were far less in the case of in-place recycling, although the environmental loads sometimes increase when the machines for the in-place recycling need to be transported long distances. Thus, recycling methods should be selected in consideration of environmental loads.

INTRODUCTION

As global warming and other environmental issues have gained greater attention, various efforts have been made to develop technologies for reducing environmental load in diverse fields. Recycling is one such means, and in the field of pavement in Japan, aggregate has been recycled for a long time. At present, asphalt pavement aggregates removed from paved roadways are recycled 99% (Figure 1).¹⁾

Pavement recycling methods in Japan include plant recycling and in-place recycling, with the majority currently done by plant recycling. These recycling endeavors have increased year by year (Figure 2)²⁾. Nevertheless, regarding global warming and various environmental load matters in particular, their effectiveness has not yet been fully identified. Although the CO₂ emissions involved in pavement recycling have been examined,³⁾ the details of recycling methods and estimation conditions were not clearly, and the environmental loads throughout the lifecycle including materials production, transportation, construction, and waste disposal have not yet been identified.

This paper reports on the results of estimating the amount of environmental loads those are CO₂ emissions, energy consumptions, SO_x emissions, NO_x emissions and SPM emissions in this study, generated by pavement repair works using either conventional plant recycling or in-place recycling which reportedly generates less environmental loads. Hence the key environmental impacts of each construction method were determined and the three treatments were compared.

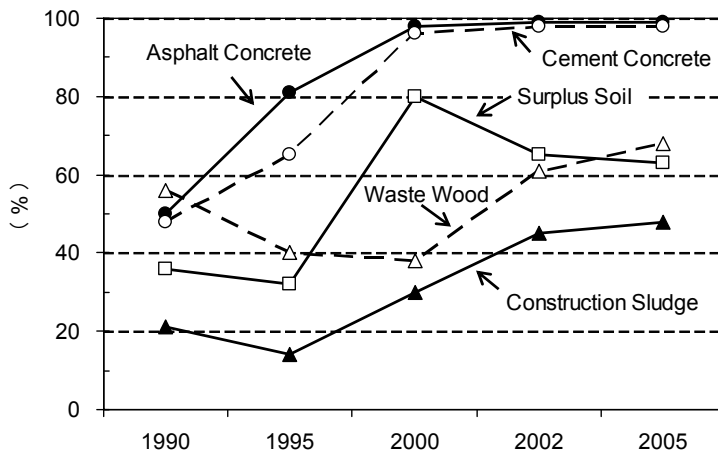


Figure 1 The percentage of recycled resources from construction by-products¹⁾.

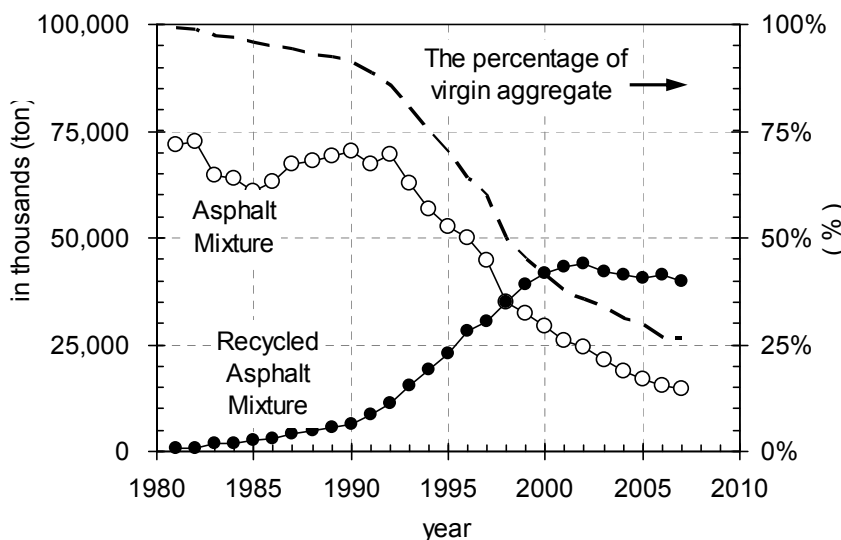


Figure 2 The amount of shipment of asphalt mixture²⁾.

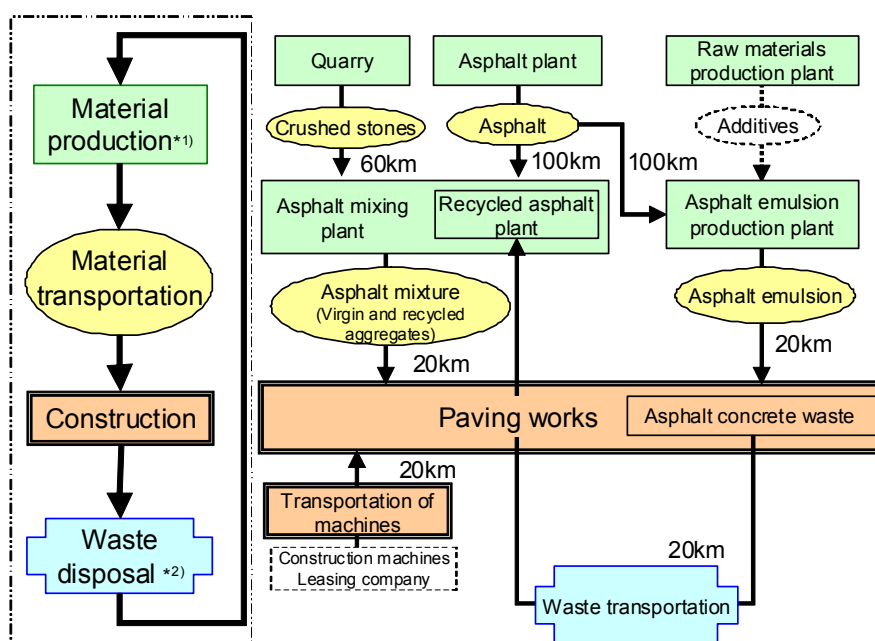
OUTLINE AND CONDITIONS OF ESTIMATION

The pavement repair work methods used for estimating the environmental loads in this study were cut-and-overlay, which is a general method using plant recycling with recycled aggregates. The other method is in-place surface course recycling, which is an in-place recycling method. Some variations were made to the case studies for comparing various effects, e.g., the use of virgin aggregates and recycled aggregates, change of the mix ratio of recycled aggregates, and transportation of machines specially designed for the in-place surface course recycling in various places nationwide.

The cycle from materials production to waste disposal for pavement repair works was examined, the quantities of materials, machines, and fuel used or consumed were estimated. The estimated figures were multiplied by the Cumulative Energy Demand (CED) to obtain the amount of environmental loads. “CED” indicates the total amount of energy consumption such as electric power and fuel which is needed for producing unit amount of materials, and the total amount of environmental emissions. CED of all environmental loads obtained by the process analysis method, were selected from existing literature for this study. When unavailable in the existing literature, the CED of environmental loads was determined by interviewing manufacturers.

Range of estimation

The stages of pavement works examined in this study were set up as shown in **Figure 3**, being classified by the stages of CO2 emissions, i.e., material production, material transportation, construction, and waste disposal.



Notes: *1) Material production includes the process from acquisition to processing of raw materials.

*2) Waste disposal means the transportation of asphalt concrete waste (transportation of waste materials to the plant for producing recycled aggregates).

Figure 3 Range for examining the environmental loads of pavement works.

In consideration of the present circumstances in Japan, the distance of transporting materials was set as 100 km for asphalt, 60 km for crushed stones (virgin aggregates), and 20 km for asphalt mixture. In Japan, almost of all recycled asphalt plant is setting up with asphalt mixing plant. These are average distances, and may vary by region.

Regarding waste disposal, all asphalt concrete waste were considered to be transported to a plant that produces recycled aggregates, since almost all aggregates of existing asphalt pavements are being recycled today.

As shown in **Table 1**, estimations were conducted using cut-and-overlay and in-place surface course

recycling by following three cases. Case 1: cut-and-overlay using virgin aggregates; Case 2: cut-and-overlay using recycled aggregates produced at a recycled asphalt plant; and Case 3: in-place surface course recycling (remix method).

The mix ratio of recycled aggregates in RAP was set to 60% in Case 2 based on the average in urban areas in Japan.

Table 1 Cases used for estimation

Cases	Examination of methods for repairing the surface course		
	Case 1	Case 2	Case 3
Repair method	Virgin aggregates (control) (Cut-and-overlay)	Plant recycling method	In-place surface course recycling method (Remix)
Replacing thickness	Cutting off the existing pavement by 3 cm in thickness and overlaying new pavement with 5 cm in thickness		
Mix ratio of recycled aggregates	0%	60%	(60%)

Scale of paving works

The paving works were conducted on a 3.25 m-wide, 200 m-long, 2-lane roadway (work area of 1,300 m²). The existing asphalt pavement of 3 cm in thickness was cut out, and new pavement of 5 cm in thickness was overlaid. Commonly the in-place recycling is applied for much longer construction distance. However, according to calculation of the quantity of materials and number of machines used which is mentioned below indicates that the scale of paving work is not affected. Therefore all work area was standardized by about 1,000 m².

Quantity of materials and machines used

The quantity of materials and number of machines used for paving works, as well as the amount of fuel consumption, were calculated based on the scale of paving works, the amount of materials transported, and the Manual of Standard Quantity Surveying for Civil Engineering Works compiled by the Ministry of Land, Infrastructure, Transport and Tourism of Japan (MLIT)⁴⁾ and other references. This manual was created to enable government and other public offices to conduct quantity surveys to estimate construction costs, as well as the conditions of materials to be used for public works, appropriate machines for respective pavement methods, and the quantities required.

The fuel consumption of road heaters used for in-place surface course recycling was set based on interviews with paving companies, because such interviews showed that it greatly varied depending on the machine.

CED of environmental loads

The CED of environmental loads of materials used for paving works were determined using figures already published or registered in existing databases, which had been obtained by the process analysis method as shown in **Table 2**.

As there were no figures for asphalt emulsion in the literature, producers were interviewed. Consequently, the Asphalt emulsion was made by asphalt, water, hydrochloric acid, and surfactant. The composition ratio was 50:48:1:1. The power consumed by the emulsifying machineries for mixing constituents was set to 0.03 kWh/kg. The transportation of hydrochloric acid and surfactant was not taken into consideration because the fuel consumption was negligible.

As for other materials not shown in **Table 2**, rejuvenators for RAP could be used as an option. In the reference⁵⁾, from which the CED of environmental loads of asphalt were determined, the CED of environmental

loads of all refined petroleum products are the same. Accordingly, the CED of environmental loads of rejuvenators was considered to be roughly the same, and so the amount of rejuvenators used was included in the amount of asphalt.

Table 2 CED of environmental loads

Item	(Unit)	Energy (MJ)	CO ₂ (kg)	SOx (kg)	NOx (kg)	SPM (kg)	Source
Electric power	kWh	9.09E+00	4.00E-01	5.15E-05	1.62E-04	1.72E-06	JEMAI-LCA*1
Gasoline	L	3.51E+01	2.47E+00	7.57E-05	7.61E-04	8.62E-05	
Diesel	L	3.82E+01	2.69E+00	8.24E-05	8.29E-04	9.39E-05	
Asphalt	kg	4.33E+00	2.48E-01	1.64E-03	1.14E-03	—	Reference 5
virgin aggregates	t	8.89E+01	5.39E+00	8.35E-04	2.02E-03	1.52E-04	Reference 6
Recycled aggregate	t	3.41E+01	2.08E+00	1.94E-04	7.80E-04	6.01E-05	
Asphalt mixture	t	4.48E+02	2.91E+01	1.26E-02	9.65E-03	9.33E-04	
Recycled Asphalt mixture	t	5.00E+02	3.28E+01	1.45E-02	1.07E-02	1.07E-03	
Asphalt emulsion	kg	2.43E+00	1.60E-01	8.30E-04	5.89E-04	1.35E-06	
Industrial water	m ³	5.69E+00	1.00E-01	1.31E-05	3.95E-05	5.56E-07	JEMAI-LCA*1
Hydrochloric acid	kg	—	1.08E+00	7.19E-04	4.70E-04	1.07E-04	JEMAI-LCA*1
Surfactant	kg	—	1.03E+00	—	7.20E-04	2.35E-05	Reference 7*2

Note: *1) JEMAI-LCA is a LCA software developed by the Research Center for Life Cycle Assessment, National Institute of Advanced Industrial Science and Technology (AIST) and Japan Environmental Management Association for Industry (JEMAI).

*2) The CED of coconut oil fatty acid was used as a substitute for that of surfactant, because appropriate figures for constituents and production processes of surfactant were not available.

Set up weighting factor for environmental loads

It is unknown that how each environmental load materials have effect on environment. Beside each of them cannot compare. Therefore, this study examined to integrate each environmental load. For choosing weighting factor as integration, several indices are suggested. In this case, LIME’s integration factor⁸⁾ which is developed in Japan is used. LIME stands for “Life-cycle Impact assessment Method based on Endpoint modeling”.

This method convert different environmental loads items into cost of environmental damage, then various items come into same index (JPY).

Table 3 LIME’s integration factor⁸⁾

	Energy (JPY/MJ)	CO ₂ (JPY/kg)	SOx (JPY/g)	NOx (JPY/g)	SPM (JPY/g)
LIME’s integration factor	0.0666	2.18	1.0773	0.1891	0.00245

RESULTS OF ESTIMATING THE ENVIRONMENTAL LOADS

Table 5 shows the results of estimating the material consumption in the respective cases based on the scale of pavement works established in “Scale of paving works”, as well as the quantities of materials and machines used and their fuel consumption established in “Quantity of materials and machines used”.

The environmental loads were estimated (**Figure 4**) by multiplying the amount of material consumption by the CED of environmental loads (**Table 2**). The results were classified the environmental loads into the respective emission stages in pavement works, i.e., “Material production”, “Material transportation”, “Construction” and “Waste disposal”. A rate of emission of SOx and NOx is numerous when producing materials. This is because CED of asphalt for SOx and NOx is larger than consumption fuel of CED such as gasoline and light oil.

Table 2 Amounts of material consumption in the respective cases

Emission stage	Quantity of materials				
	Case 1	Case 2	Case 3		
Material production	Asphalt mixture	163.4 t	163.4 t	61.1 t	
	Asphalt	8.9 t	3.6 t	3.4 t	
	Crushed stone (virgin material)	154.5 t	61.8 t	57.7 t	
	Recycled aggregate	-	98.0 t	-	
	Asphalt emulsion	1,638.0 L	1,638.0 L	705.7 L	
Material transportation	Diesel	1,187.2 L	646.0 L	482.0 L	
Construction	Machine transportation	Diesel	99 L	99 L	100.0 L
		Diesel	300.9 L	300.9 L	295.2 L
	Paving work	Kerosene*	-	-	1,560.0 L
		LPG*	-	-	1.3 t
Waste disposal	Waste transportation	Diesel	131.2 L	131.2 L	-

Note:* Kerosene and LPG fuels are used for the road heater (for heating), for which average figures are used for environmental loads.

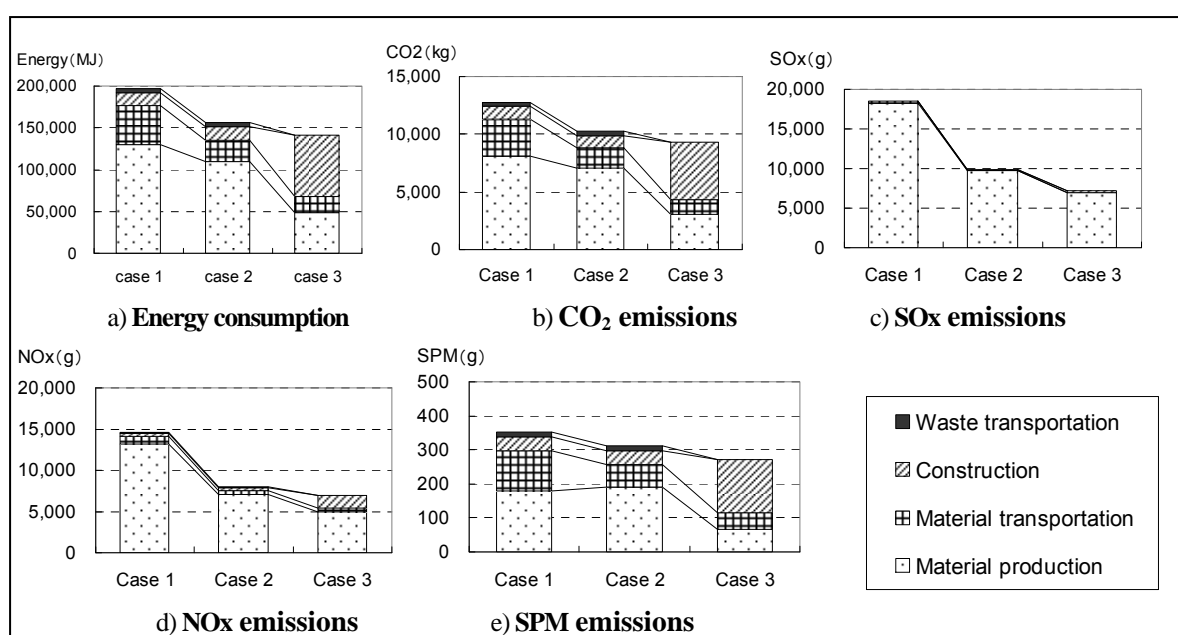


Figure 4 environmental loads in the case1 to 3.

Estimation by integration

By integration, this study comparing whole amount of environmental loads, and considering influential loads materials. **Figure 5** shows the result of whole amount of environmental loads which is multiplied environment load (**Figure 4**) in various cases by Lime’s coefficient (**Table 4**). It shows that the total amount of environmental loads of case 2 comes 70% of case1. In case 3, it comes 60% of case 1.

According to each ratio of environmental loads material, CO₂, SO_x and energy are more influenceable against environment. Therefore, when discussing about the amount of environmental loads in paving works, it is important to consider those three items.

Next, **Figure 6** shows the result of the integration of environmental roads which is classified by each stages for emission such as “material production”, “material transportation”, “construction”, and “waste disposal”.

As a result, it showed that the environmental loads in the stage of material production were the greatest in all three cases, and in particular the environmental loads in Cases 1 and 2 accounted for approximately 70% of the total. Regarding the stage of material transportation, the CO₂ emissions in Case 2 accounted for 60% of that in Case 1. The environmental loads decreased because the use of recycled aggregates in place of virgin

materials reduced the transportation distances. The departure point of transportation was changed from the quarries to the paving work site. In Case 3, the environmental loads during paving work execution were greater even though waste transportation was not required and less material transportation was needed than in Cases 1 and 2.

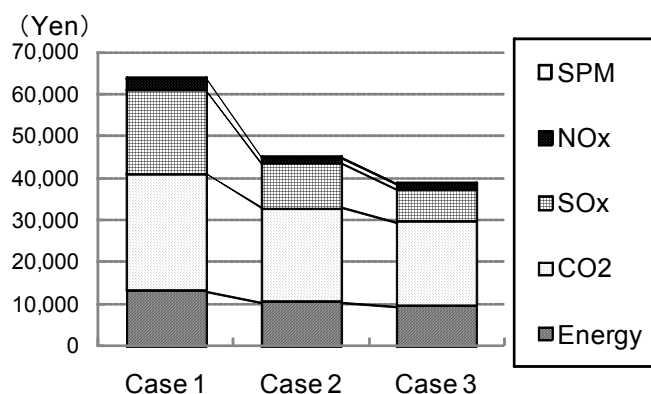


Figure 5 Integration of environmental loads by each item.

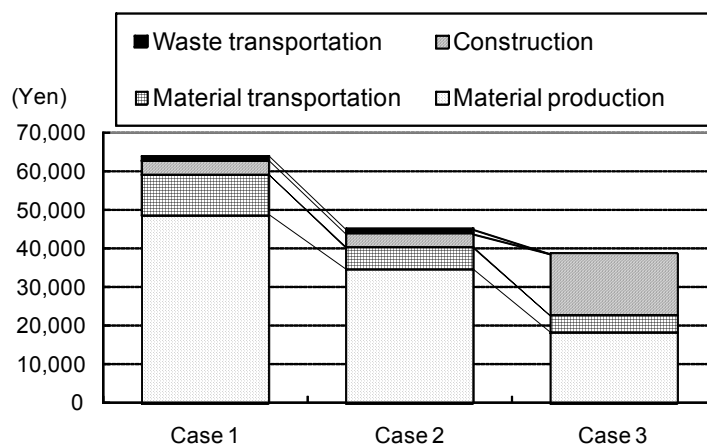


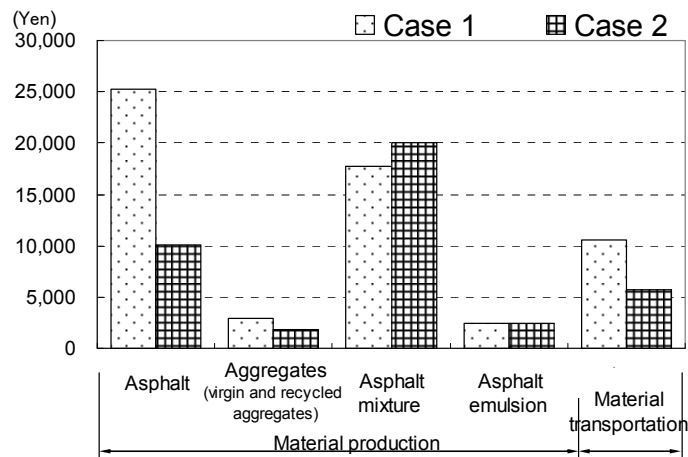
Figure 6 Integration of environmental loads by each stage.

Comparison between virgin aggregates and recycled aggregates with cut-and-overlay

Concerning the cut-and-overlay, the amount of environmental loads was compared between Case 1 which used virgin aggregates and Case 2 which used recycled aggregates.

As the work process in Cases 1 and 2 from the stage of construction (paving work, and machine transportation) to the stage of waste disposal is identical, the amount of environmental loads is the same in these two cases. Accordingly, the environmental loads from the stage of material production to the stage of material transportation were compared (Figure 7). The material production stage comprises the production of asphalt, aggregates, asphalt mixtures, asphalt emulsion. The results showed that the production of asphalt and asphalt mixture accounted for most of the environmental loads in this stage.

The CED of environmental loads show in Table 2. It shows that the production of virgin aggregates is greater than recycled aggregates. However, the production of recycled asphalt mixture is greater than asphalt mixture using virgin aggregates. Thus, in the initial stage of our study, it was uncertain which cases are greater amount of environmental loads when using recycled aggregates or using virgin materials. In fact, the environmental loads during asphalt mixture production in Case 2 were greater than in Case 1. Nonetheless, the total environmental loads during material production were actually decreased because the decrease in the environmental loads of asphalt surpassed the increase in the environmental loads mentioned above. Furthermore, the total environmental loads in Case 2 were less than in Case 1 thanks to the reduction in material transportation.



(For the material production and material transportation stages)

Figure 7 Comparison of environmental loads between Cases 1 and 2.

Effect of the difference in the mix ratio of recycled aggregates in plant recycling on the environmental loads

The effect of the mix ratio of recycled aggregates on the environmental loads in Case 2 was estimated. This mix ratio was initially set to 60%, which is the average in urban areas, and estimation was also conducted for the mix ratio of 40% which is the nationwide average including local areas, and for the mix ratio of 80% assuming that the recycling rate will probably increase in the future.

Figure 8 shows the results of the estimation. The overall environmental loads are shown by bars, and the quantities are shown on the right axis. In addition, the environmental loads of asphalt, aggregates (virgin and recycled aggregates), and asphalt mixture during material production, which change with the mix ratio of recycled aggregates, as well as those during material transportation, were extracted and plotted by broken lines.

These lines show that the environmental loads during recycled aggregates production gradually increased, but those of the asphalt production decreased greatly. As for the aggregate production, the environmental loads are almost same when virgin aggregates were used instead of recycled aggregates. The decrease in environmental loads of asphalt production was due to the amount of asphalt used was decreased because of the mix ratio of recycled aggregates was increased. On the other hand, the decrease in environmental loads during material transportation was due to the decrease in the fuel consumption of trucks for transporting virgin aggregates and asphalt. Consequently, total environmental loads decreased.

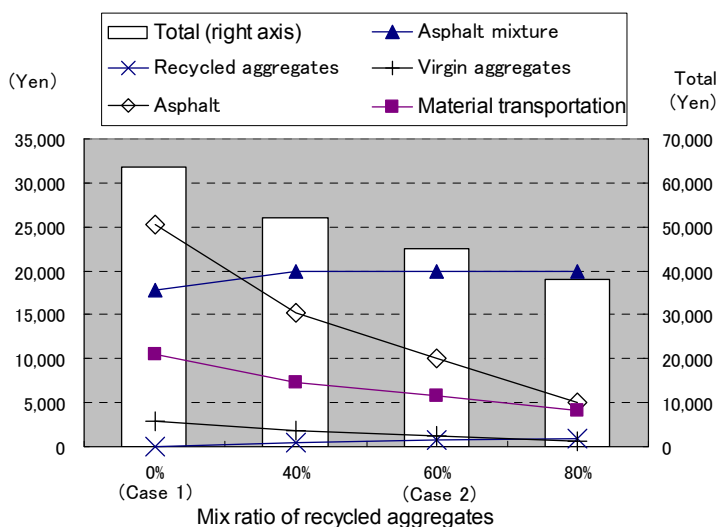
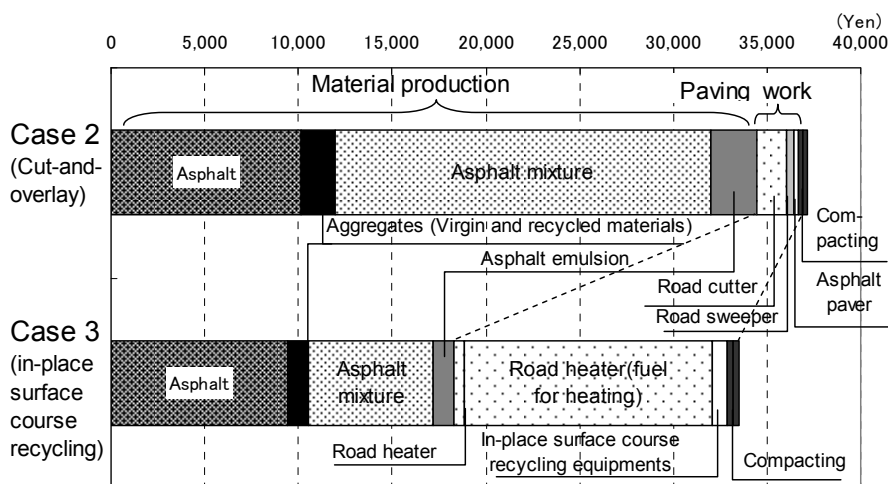


Figure 8 Comparison of CO₂ emissions by the mix ratio of recycled aggregates.

Comparison between cut-and-overlay and in-place surface course recycling

As shown in **Figure 6**, the amount of environmental loads was estimated to be small for in-place surface course recycling in Case 3. However, the environmental loads of construction were considerably high in comparison with cut-and-overlay in Cases 1 and 2. This is because, with the in-place surface course recycling, a series of paving processes, including heating and pulverizing the existing pavement and mixing it with virgin asphalt mixture, are done on site. Specifically, these two paving methods cannot be compared based only on the environmental loads emissions during work execution, because the production of recycled aggregates and asphalt mixture is included in the stage of material production in the case of cut-and-overlay, while it is included in the stage of paving works in the case of in-place surface course recycling.

Therefore, these two paving methods were compared by extracting the environmental loads in the stages of material production and paving works (**Figure 9**). As a result, the amount of these environmental loads was almost same. Moreover, the environmental loads of in-place surface course recycling are smaller, because this method requires the transportation of no waste but only a small amount of materials, thereby reducing the total environmental loads.



(For the material production and paving works stages)

Figure 9 Comparison of environmental loads between Cases 2 and 3.

However, there are not enough in-place surface course recycling machines nationwide, so the equipment must sometimes be transported long distances to other sites. Therefore, the effect of transportation distance on environmental load was examined. The calculations assumed that the in-place surface course recycling equipment was transported overland by a 25 t dump truck powered by diesel with a mileage of 19.720 L/h when driven at 25 km/h for distances of 500 km or 1,000 km. Specifically, only the diesel fuel consumption required for transportation was set to 25 times and 50 times the basic case (20 km) in proportion to the distance covered. In addition, as fuel-efficient road heaters (for heating) have recently been developed, a case with minimum fuel consumption was estimated. The results are shown in **Figure 10**.

The environmental loads in Case 3, for which the average road heater fuel consumption was used, were equivalent to those in Case 2 when the distance covered were approximately 500 km. This showed that even in-place surface course recycling generates large environmental loads due to transportation of equipment and machines.

The line of environmental loads of the case with minimum fuel consumption crossed the line of Case 2 at a distance of approximately 800 km. Hence, fuel-efficient road heaters will lessen the environmental loads, and the difference in fuel consumption efficiency of road heaters greatly affects the environmental loads.

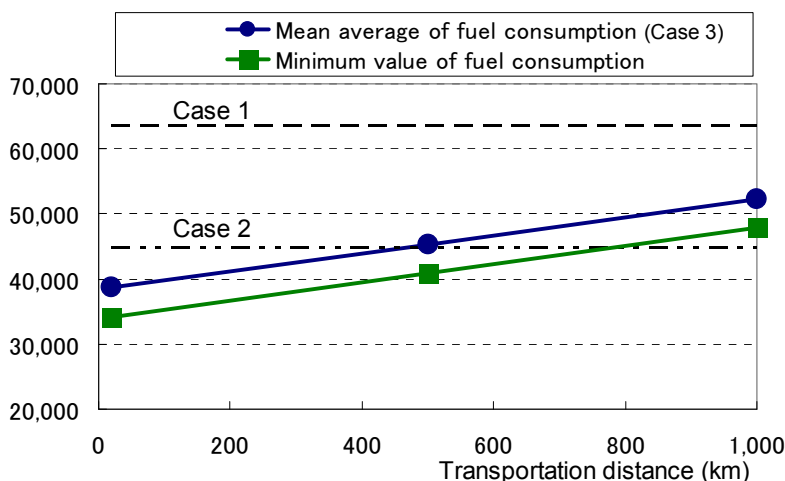


Figure 10 Comparison of in-place surface course recycling equipment by transportation distance.

CONCLUTIONS

The results of this study are summarized below.

1) Concerning the environmental loads in the respective emission stages from material production to waste disposal for the cut-and-overlay and in-place surface course recycling methods, the material production stage accounted for a high proportion of the emissions. With the cut-and-overlay in particular, the environmental loads in this stage accounted for approximately 70% of the total. Concerning the material production stage, environmental loads due to the production of asphalt mixture and asphalt were particularly great.

2) A comparison of environmental loads between virgin aggregates and recycled aggregates with cut-and-overlay showed that total environmental loads were less when recycled aggregates were used because the quantity of asphalt used and the quantity of aggregates transported were reduced, although the environmental loads during the production of aggregates and asphalt mixture were greater than when virgin aggregates were used.

3) When the stages of asphalt mixture production and paving works were included, the environmental loads with in-place surface course recycling were greater than with cut-and-overlay, for a recycled aggregates mix ratio of 60%. Nevertheless, the total amount of environmental loads with in-place surface course recycling was small, because the environmental loads during material transportation were small and because no waste material transportation was required.

4) Even with in-place surface course recycling which generates less environmental loads, environmental loads may increase depending on the distance that in-place surface course recycling equipment must be transported.

Future problems to be studied include the following:

1) The environmental loads generated by the machines used are greatly affected by those generated during the production of road cutters and in-place surface course recycling equipment. This was not considered in the present study and so should be considered in future studies.

2) The service life of pavement may vary depending on the use of either virgin or recycled materials, the use of either plant recycling or in-place recycling, and the use of various other paving technologies to supplement the pavement. Thus, environmental loads should be estimated for the long term including the service life of pavement.

3) Changes of environmental loads due to the combined use of energy-saving technologies during material production must be estimated. One such technology is the warm-mix technology, which is known to reduce CO2 emissions by lowering the heating temperature when producing asphalt mixture to reduce the fuel consumed for heating. Accordingly, the increase in environmental loads for producing the warm-mix additives themselves must be examined.

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