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An Integrated Concrete Recycling System Including Cement

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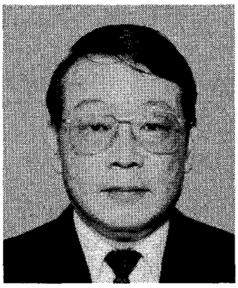

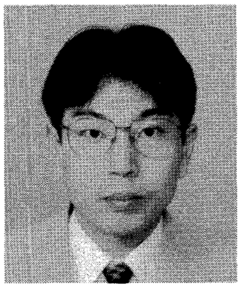

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This report presents a new approach to the recycling of concrete for the 21st century. When demolished concrete is processed by a heating method, the resulting aggregate is unbroken and of satisfactory quality for use in concrete. The chemical composition of the powder that results from this processing is estimated, and the possibility of recycling it as cement, thereby reducing limestone requirements, is demonstrated. If concrete is recycled by this method into both cement and aggregate, resources and carbon dioxide emissions are reduced. In the near future, external diseconomies like these will come to be reflected the cost of products, and concrete recycling methods that include recovery of cement will be needed reduce such external diseconomies.

Keywords: *concrete, recycling, external diseconomies, reclaimed cement, resources, energy, carbon dioxide emissions*

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1. INTRODUCTION

The concept of sustainable development is proposed as a way to protect our finite and deteriorating planet. This concept involves reducing environmental loading as much as possible and building a society-based recycling system [1]. In the concrete industry, methods of recycling are currently being studied for demolished concrete. This material is already reused as a road base course and foundation material, and a great deal of research is being conducted to find ways of recycling demolished concrete as concrete aggregate. In any recycling scheme for concrete, there is no doubt that a closed recycling system that turns old concrete back into new would be desirable. Fully recyclable concrete using limestone aggregate has been proposed as special type [2].

This paper verifies the possibility of reclaiming cement from demolished concrete and shows a target direction for concrete recycling by evaluating resource consumption, energy requirements, and carbon dioxide emissions in concrete manufacturing.

2. STATE OF RECYCLING

According to the Ministry of Welfare, 400 million tons of industrial waste have been produced each year since 1990 in Japan [3]. Intermediate treatment is gradually being promoted. As a result of a 46% reduction in the amount of waste material and 37% recycling, the quantity of waste going for final disposal is 68 million tons, corresponding to 17% of the total generated. However, the capacity of final disposal sites is 200 million cubic meters and this will be exhausted in only three years. The construction industry is a major source of industrial waste, producing about the 19% of the total. In this, it ranks with the electrical-gas-water supply industry and agriculture.

A survey conducted by the Ministry of Construction in 1995 clarified that the total quantity of construction waste produced each year had reached 99 million tons, with 1% reduction of the total, 57% recycled, and 42% going to final disposal [4]. Cement-concrete lumps account for 37 million tons (37%) of this construction waste, and asphalt-concrete lumps are 36 million tons (36%). The recycling ratio is relatively large, at 65% and 81% respectively. However details of the recycling process are slightly different.

In the case of asphalt concrete, it can be relatively easily broken up by simply heating, so recycling has long been the norm. It is possible to turn old asphalt concrete back into new. On the other hand, the current situation is that concrete can only be recycled into road base course and foundation materials. Such reuse of concrete as a road base course and foundation material is effective for the preservation of resources and nature. However, as the quantity of waste concrete resulting from demolition is expected to increase and demand road base material unlikely to increase in the future, efforts are under way to develop ways of using recycled aggregate in concrete.

When demolished concrete is recycled into concrete aggregate, the handicap is the presence of mortar adhering to the original aggregate. If all of this mortar is removed, a large amount of powder is produced, and disposal becomes a major problem. On the other hand, if the aggregate is not fully cleaned of mortar, the recycled product does not satisfy the quality requirements for concrete aggregate. This limits its use in concrete. At the same time, it is also a fact that recycling into aggregate is economical and the amount of powder produced has been considerably reduced. Given this situation, there is a need for clarification of the characteristics of concrete made with recycled aggregate that includes adhered mortar. Many investigations related to this topic are under way now.

3. ECONOMICS OF THE RECYCLING SYSTEM

Most of arguments based on economics point out the high cost of recycled products, and their inferior quality compared to virgin materials. There are several reasons for the high cost. The first reason is simply that there is as yet no recycling system in place in our society. Redesigning society to accommodate this new concept and building the necessary conditions for recycling (reclaiming, distribution, and marketing) lead to a temporary increases in cost. Secondly, and more essentially, the external diseconomies of using virgin materials have been noted.

The concept of external diseconomies was first recognized in economics about 100 years ago [5]. For example, the cost of a product that involves the discharge of toxic materials in its manufacture is artificially low as a result of external diseconomies. The range of activities that should be treated as external diseconomies depends on the scale of human activity. On an infinite and deterioration-free planet with little activity, the disruption of nature resulting from mining resources and emitting carbon dioxide are not treated as external diseconomies. However, now that it is clear our planet is finite and deteriorating as a result of expanding human activity, ruin will come unless external diseconomies are fully taken into account and reflected in the internal economy.

The field of environmental economics has already become established [5], and companies are adopting the ideas of "environmental accounting" [6]. Evaluations of environmental issues in terms of money have been attempted. Also the external diseconomies of virgin materials are estimated in connection with construction [7]. However, it is not easy to correctly estimate the external diseconomies. Environmental accounting attempts to estimate external economies by calculating the cost of countermeasures for the environment. A standard evaluation method for external economies will soon be fully established. Once this is achieved, the method should be applicable to the estimation of external diseconomies. The estimation of external diseconomies will be reflected in product cost as an environmental tax.

It is certain that human population and activity will increase as time passes, and the estimated value of external diseconomies in the environment will increase. If a new recycling concept is developed by taking into account the external diseconomies affecting the environment, recycling will certainly become economical in the future.

4. CONCEPT OF RECYCLING

The expectations of a recycling system in which demolished concrete is used as raw material for cement have already been expressed in recent reports [8]. In fact, the possibility of attaining fully recyclable concrete has been discussed for the special case where the demolished concrete is made of limestone aggregate [2]. However, this approach cannot be employed for the recycling of the existing concrete structures. The use of powder generated when recycling of aggregate to produce cement clinker has been discussed from several perspectives. However, this idea is limited to the substitution of this powder for clay only [9]. The reason for this limitation is that aggregate powder contains many by-products from the recycling of aggregate by ordinary mechanical crushing.

Against the background of these ideas, the priority has switched to a focus on cement reclamation from demolished concrete. If as much of the cement-containing powder as possible can be collected, high-quality aggregate will also result. One method of recycling aggregate from concrete involves using a thermal treatment to weaken the paste components [10]. According to a recent report on this method, the recycled aggregate meets the quality requirements of both fine and coarse concrete aggregates, and in the case of coarse aggregate is almost completely unbroken [11]. Although the report makes no mention of the composition of the remaining powder, it can be assumed that cement is its major constituent.

5. ASSESSMENT OF CEMENT RECLAMATION

5.1 Estimation of chemical composition of the powder

According to a report by a committee on promotion of construction by-products in the Japan Cement Association [9], the chemical composition of the powder produced by aggregate recycling plants is as shown in Table 1. It is clear that the powder consists of cement and aggregate. The chemical composition of normal Portland cement is shown in Table 2. It is assumed that the CaO and SO_3 in the powder originate from the hydrated cement. Estimated chemical compositions of aggregate powders are given in Table 3. Assuming that the chemical composition of the aggregate-derived part of the powder is the mean of the values presented in Table 3, the chemical composition of the recycled powder would be as calculated in Table 4. On the other hand, a report on the crushing of concrete after thermal treatment [11] estimates the aggregate content in the powder as shown in Table 5. This is the result of grinding of the aggregate, and so the following studies will be conducted on the assumption that the aggregate ratio can be reduced to 30%.

Table 1 Chemical composition of powder from recycling plants (%)

Source	Ig. loss	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2Oeq	Cl
A	6.0	54.6	13.8	5.4	9.1	3.8	0.2	2.99	0.022
B	10.2	48.6	11.6	5.3	17.0	3.7	0.5	2.46	0.042
C	11.7	50.8	9.9	4.3	17.7	1.7	0.7	2.46	0.024
D	13.2	49.3	8.2	2.6	20.7	1.3	0.8	1.92	0.039
E	13.0	44.2	8.7	3.7	25.4	1.7	0.7	1.85	0.206
F	17.1	44.2	11.4	3.5	18.7	1.4	0.5	2.30	0.021
G	10.0	50.7	10.5	2.7	18.9	1.8	0.5	2.48	0.073
H	11.3	47.7	11.7	2.8	20.0	2.0	0.7	1.93	0.024
I	9.2	57.8	10.1	3.5	14.5	0.9	0.5	2.63	0.023
J	10.4	59.6	8.3	2.7	14.4	0.8	0.2	2.58	0.007
K	7.1	61.3	9.7	1.9	15.0	0.7	0.5	2.88	0.015
L	7.6	54.9	10.4	3.2	18.5	2.0	0.6	1.93	0.081
M	14.8	46.3	9.1	3.0	21.5	1.2	0.7	2.60	0.044
N	16.0	40.0	8.7	3.1	27.5	1.4	0.5	2.11	0.038

Table 2 Chemical composition of normal Portland cement (%)

	Ig. loss	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2Oeq	Cl
Normal Portland cement	0.7	22.2	5.2	3.1	64.8	1.5	1.9	0.70	0.005

Table 3 Chemical composition of aggregate (%)

Source	Ig. loss	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2Oeq	Cl
A	3.9	65.1	16.5	6.3	0.0	4.5	-0.1	3.65	0.027
B	7.0	63.0	15.1	6.6	0.0	4.9	0.0	3.35	0.060
C	9.1	67.3	12.7	5.2	0.0	1.9	0.3	3.41	0.034
D	11.1	70.7	10.9	2.7	0.0	1.4	0.3	2.84	0.063
E	9.4	67.7	12.7	4.7	0.0	2.1	0.0	3.01	0.389
F	17.3	58.6	15.3	4.0	0.0	1.5	-0.1	3.25	0.030
G	6.3	70.6	14.3	2.9	0.0	2.2	-0.1	3.64	0.114
H	8.1	66.8	16.5	3.0	0.0	2.5	0.2	2.80	0.037
I	6.3	73.1	12.4	3.9	0.0	0.8	0.1	3.42	0.030
J	8.0	75.6	9.9	2.8	0.0	0.6	-0.3	3.35	0.008
K	3.3	78.7	11.9	1.7	0.0	0.5	0.1	3.81	0.019
L	2.6	74.7	13.7	3.6	0.0	2.4	0.1	2.66	0.122
M	13.4	65.5	12.4	3.3	0.0	1.2	0.1	3.98	0.071
N	14.9	63.2	13.4	3.7	0.0	1.6	-0.6	3.75	0.074
Mean	8.6	68.6	13.4	3.9	0.0	2.0	0.0	3.35	0.077

Table 4 Chemical composition of recycled powder (%)

Aggregate ratio (%)	Ig. loss	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2Oeq	Cl
20	2.2	31.5	6.8	3.3	51.8	1.6	1.5	1.23	0.019
30	3.0	36.1	7.7	3.3	45.4	1.7	1.3	1.50	0.027
40	3.8	40.8	8.5	3.4	38.9	1.7	1.1	1.76	0.034
50	4.6	45.4	9.3	3.5	32.4	1.8	0.9	2.03	0.041

Table 5 Aggregate ratio of recycled powder by thermal treatment

	Water	Cement	Fine aggregate	Coarse aggregate	Powder
Concrete (kg/m^3)	157	314	802	1030	
Collecting ratio (%)			87.5	93.54	
Quantity (kg/m^3)			702	963	481
Aggregate ratio (%)					35

5.2 Cement Reclamation

Taking into account the chemical composition of cement clinker as reported by the construction by-product promotion Committee of the Japan Cement Association [9], the estimated chemical composition of normal Portland cement is as presented in Table 6. Hydraulic modulus, silica modulus, and iron modulus are 2.09, 2.68, and 1.67, respectively. This chemical composition satisfies the specification of JIS R 5210, the standard for normal Portland cement.

Table 6 Normal Portland cement made with virgin materials

		Chemical composition (%)									Quantity
		Ig. loss	SiO2	Al2O3	Fe2O3	CaO	MgO	SO3	Na2Oeq	Cl	(kg)
Clinker	Limestone	43.0	1.1	0.3	0.3	54.2	0.5	0.0	0.03		1142
	Clay	7.8	64.3	14.1	5.1	2.7	1.7	0.2	2.63		244
	Silica	1.3	91.1	4.1	1.5	0.1	0.5	0.0	0.69		32
	Iron slag	9.1	16.4	5.3	54.4	9.4	1.5	1.7	0.53	0.189	29
	B. F. slag		39.2	13.1	1.2	38.7	4.9	1.7	0.61	0.003	111
	Fly ash		55.4	31.1	6.5	3.0	1.3	12.0	2.44		14
	Total	32.1	14.6	3.4	2.0	42.0	1.0	0.3	0.46	0.004	1572
Cement	Clinker	0.0	22.9	5.3	3.2	65.9	1.5	0.4	0.72	0.006	1003
	Gypsum	(20.9)				32.6		46.5			32
	Cement*	0.7	22.2	5.2	3.1	64.8	1.5	1.9	0.70	0.005	1000
JIS R 5210 N.P.C		<3.0					<5.0	<3.0	<0.75	<0.02	

* HM=2.09, SM=2.68, IM=1.67

Table 7 shows the results that indicate how the quantity of limestone can be reduced when recycled powder with an aggregate ratio of 30% (Table 4) is used as clinker raw material to adjust the hydraulic modulus, silica modulus, and iron modulus to 2.05, 2.88, and 1.66, respectively. The value for Na2Oeq slightly exceeds JIS R 5210, the standard for normal Portland cement, but in principle the recycling of powder to make cement appears to be possible.

Table 7 Normal Portland cement made with recycled powder

		Chemical composition (%)									Quantity
		Ig. loss	SiO2	Al2O3	Fe2O3	CaO	MgO	SO3	Na2Oeq	Cl	(kg)
Clinker	Limestone	43.0	1.1	0.3	0.3	54.2	0.5	0.0	0.03		668
	Recycled powder	3.0	36.1	7.7	3.3	45.4	1.7	1.3	1.50	0.027	622
	Iron slag	9.1	16.4	5.3	54.4	9.4	1.5	1.7	0.53	0.189	15
	Total	23.5	17.7	3.8	2.3	49.2	1.1	0.6	0.73	0.015	1325
Cement	Clinker	0.0	23.4	5.1	3.1	65.2	1.4	0.8	0.96	0.020	1000
	Gypsum	(20.9)				32.6		46.5			32
	Cement*	0.7	22.7	4.9	3.0	64.1	1.4	2.3	0.93	0.019	1000
JIS R 5210 N.P.C		<3.0					<5.0	<3.0	<0.75	<0.02	

* HM=2.05, SM=2.88, IM=1.66

Variations in the quality of the powder would seem to be a problem in practice. On the other hand, the quantity of limestone required for the production of cement incorporating recycled aggregate powder is considerably less than in the case of eco-cement, which is made from urban waste ash and drainage mud [12]. It is obvious that there is a growing need for research on the use recycled cement.

6. EVALUATION OF RECYCLING

Assuming that the recycled powder mentioned above can be used to produce cement, the resource needs, energy needs, and carbon dioxide emissions associated with a material flow of 1 m^3 of concrete, are evaluated.

6.1 Conditions

[Cement production]

The cements considered are the aforementioned normal Portland cement and recycled Portland cement, and the conditions were as indicated below. Carbon dioxide emissions are expressed by the commonly used measure of carbon mass (kg-C).

Resources: Mining loss for limestone, clay, and silica = 0%

Energy: For mining and pulverizing limestone and silica = 42 kJ/kg [14]
For calcination = 2954 kJ/kg of clinker [15] = 1882 kJ/kg of clinker raw material

In order to reflect the loss of decarboxylation energy and the loss of clinker raw materials, the firing energy was converted into a value per unit of clinker raw materials in calculating the energy required to calcine the recycled cement as shown above.

Carbon dioxide emissions: From limestone = 0.12 kg-C/kg [15]
From calcination = 0.0626 kg-C/kg of clinker [15]
From distribution = 0.0025 kg-C/kg of cement [16]

[Aggregate production]

Aggregates are crushed stone and crushed sand. The conditions for each are as indicated below.

Resources: Mining loss for crushed stone and crushed sand = 30% [13]
Pulverization loss for crushed stone and crushed sand = 10% [13]

Energy: For manufacturing of crushed stone and crushed sand = 42 kJ/kg [14]

Carbon dioxide emissions: From manufacture of crushed stone and crushed sand = 0.00189 kg-C/kg [16]
From distribution of crushed stone and crushed sand = 0.00056 kg-C/kg [16]

[Concrete demolition and thermal treatment]

On the assumption that the demolished concrete is transported to a place near the cement factory and then fired to 300℃ and pulverized, the conditions for the demolition and heating processes are as indicated below.

Energy: For heating process = 0.8 kJ/kg℃ × 300℃ × 1.25 = 300 kJ/kg of concrete
For demolition, transport, and pulverizing = 42 kJ/kg [14]

Carbon dioxide emissions: From heating process = 0.0161 kg-C/MJ [17]
From pulverizing = 0.00189 kg-C/kg of concrete [16]
From transport = 0.00056 kg-C/kg of concrete [16]

[Recycled concrete]

Table 8 shows the concrete mix proportions.

Table 8 Mix proportions for evaluation of concrete recycling

MSA* (mm)	Slump (cm)	Air (%)	W/C	s/a (%)	Unit content (kg/m^3)				
					Water	Cement	Fine Agg.	Coarse Agg.	AEWR
20	12.0	4.0	0.55	44	170	310	785	1015	

* maximum size of aggregate

6.2 Results and Discussion

Fig. 1 shows the material flow, energy, and carbon dioxide emissions for 1 m3 of concrete as evaluated under the conditions given above.

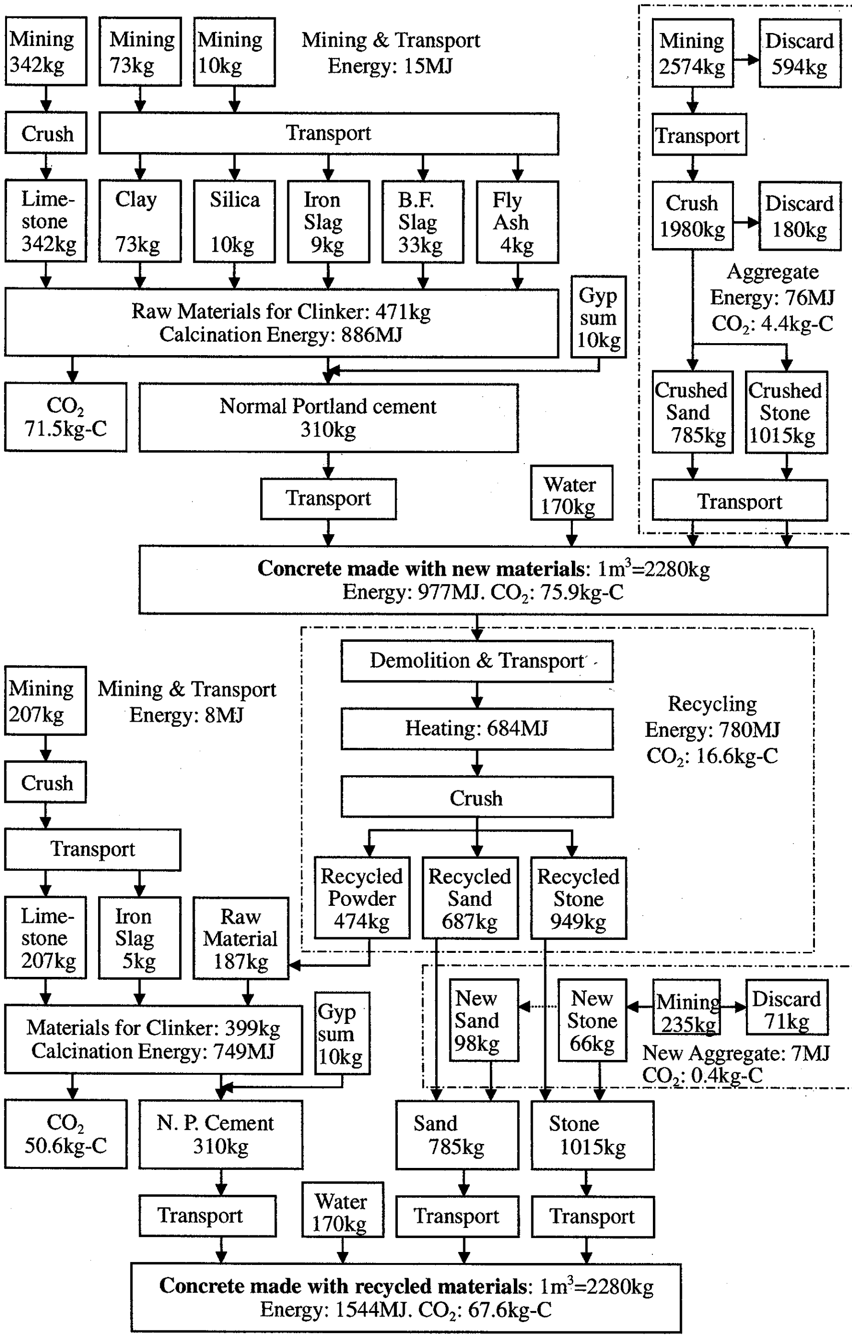

Fig. 1 Material flow for 1 m^3 concrete with energy consumption and carbon dioxide emissions

First, the use of new materials and the use of recycled materials are compared in terms of resource requirements. Table 9 shows the consumption of resources for the major components. If recycled cement is used, the amount of limestone mined decreases to 61% compared with the case where only new materials are consumed. While no clay and silica are needed, the quantities of iron slag and stone for aggregate drop to 58% and 9%, respectively. Moreover, the amount of aggregate discarded during processing is reduced from 774 kg to 71 kg (Fig. 1). When cement is recycled, of the 474 kg of recycled powder obtained, 287 kg is left over. This is a small quantity in comparison with the amount of new stone discarded, and it indicates that the refining of recycled powder is possible in terms of quantity. The recycling of cement from concrete in this way will make it possible to reduce destruction of the natural environment caused by resource mining.

Table 9 Consumption of resources (kg/concrete m^3)

	Limestone	Clay	Silica	Iron slag	Stone for Agg.
Use of new materials	342 (100%)	73 (100%)	10 (100%)	8.6 (100%)	2574 (100%)
Recycling of cement and aggregate	207 (61%)	0 (0%)	0 (0%)	5.0 (58%)	235 (9%)

Table 10 shows a comparison of the energy requirements. In the recycling of cement, the demolished concrete has to be heated, and so energy requirements are 58% greater than when new materials are used. In this study, it was assumed that the concrete would be recycled at a cement factory, and so some reduction of energy requirements can be anticipated through the use of waste heat. More radically, improvements to the cement calcinating process through the use of different raw materials are also anticipated. However, as things stand now, an increase in energy requirements is judged to be unavoidable.

Table 10 Energy requirements (MJ/concrete m^3)

	Cement production	Agg. production	Recycling	Total
Use of new materials	901 (100%)	76 (100%)	0	977 (100%)
Recycling of cement and aggregate	757 (84%)	7 (9%)	780	1544 (158%)

Table 11 compares carbon dioxide emissions. When cement is recycled, carbon dioxide emissions from cement manufacture are reduced by 29%. Even if the increase in carbon dioxide emissions due to the heating process is factored in, this still represents an overall decrease of 11%.

Table 11 Carbon dioxide emissions (kg-C/concrete m^3)

	Cement production	Agg. production	Recycling	Total
Use of new materials	71.5 (100%)	4.4 (100%)	0	75.9 (100%)
Recycling of cement and aggregate	50.6 (71%)	0.4 (9%)	16.6	67.6 (89%)

The problem of carbon dioxide emissions is a serious one for the global environment. At the Kyoto conference on global warming held in 1997 (Third Conference of the Parties to the United Nations Framework Convention on Climate Change), Japan's target for reduction of CO_2 emissions was 6%. Reducing carbon dioxide emissions caused by cement manufacture, in which large quantities of carbon dioxide fixed in limestone are discharged, would have tremendous significance.
As we have seen, a closed recycling system for concrete, in which both cement and aggregate are recycled from demolished concrete, would increase energy requirements somewhat. On the other hand, it would also conserve resources, reduce destruction of the natural environment due to mining of these resources, and reduce carbon dioxide emissions.

Even the recycling of aggregate alone would conserve certain resources and reduce the environmental destruction that results from their extraction. However, it would not reduce carbon dioxide emissions, and so this would be only a slight improvement over the current reuse of this aggregate as a road base course and foundation material. The authors contend that a concrete recycling process that includes cement and is aimed at reducing the amount of limestone used to make cement is the approach that recycling should take in the 21st century.

7. SUMMARY

(1) Conventional concrete recycling results in reuse of the materials as a road base course and foundation material, while recycling of the aggregate for use in concrete has also been attempted.

(2) As external diseconomies in the environment will come to be reflected in the cost of materials in the near future, we should be aiming at reducing external diseconomies in the environment by recycling as a way to replace the use of new materials. Thus recycling will be certainly become economic in the future.

(3) If a concrete recycling system is to include cement recycling, it is important to separate the paste from the concrete without destruction of the aggregate. If this can be achieved, the resulting recycled aggregate will be of sufficient quality for use in concrete and the problems facing recycled concrete will be solved effectively.

(4) Assuming that demolished concrete will be processed by heat treatment, the chemical composition of the resulting powder was estimated and the possibility of recycling cement with a consequent reduction in limestone requirements was demonstrated.

(5) The material flow, energy requirements, and carbon dioxide emissions related to both new and recycled concrete were evaluated. The results show that the recycling of both cement and aggregate from concrete requires more energy but uses less resources and discharges less carbon dioxide as compared with the use of new materials.

(6) For making concrete friendly to the global environment and sustainable in the 21st century, cement reclaiming should be the priority in the recycling of demolished concrete.

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