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RECYCLING MUNICIPAL SOLID WASTE INTO CONCRETE PAVING BLOCKS

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Note: The following is the notation used in this paper: (.) for decimals and ( ) for thousands.

Summary

Almost 1 kg of waste is disposed of per person a day in Japan, totaling 40 million ton or more on a nationwide scale. The waste used to be disposed of at sea or landfill sites in the mountains as it is or as incinerated ash.

To resolve the shortage of landfill sites and to control environmental pollution, the technology to recycle the waste into cement (Ecocement) and into molten slag aggregate were developed.

In May 2006, S-BIC Company Ltd. introduced the Ecocement into the base layer of the concrete paving blocks. This allowed them to consume 14 000 t of the Ecocement yearly, which is corresponding to the total waste generated by 410 000 people.

To further promote waste recycling, the concrete paving blocks using the molten slag from the municipal waste were developed.

This paper presents a study on paving block examples produced with the Ecocement (hereafter, "Ecocement" or "E") and molten slag aggregate.

1. ECOCEMENT

1.1 Ecocement features

Ecocement is designed to use municipal waste incinerator ash as up to 50% of the raw materials. It is classified into the two types shown below, depending on whether chloride ions (hereafter, "Cl^-") in the incinerator ash are removed during the manufacturing process or are used as clinker mineral.

Normal Ecocement: Having the properties similar to those of normal Portland cement with the Cl^- content reduced to 0.1% or less.

Rapid-hardening Ecocement: Using 0.5 to 1.5% Cl^- as clinker mineral to achieve rapid hardening with limited application to non-reinforced concrete.

This paper focuses on the normal Ecocement, because the Ecocement can potentially be used for the reinforced concrete.

In 2002, the standard for the Ecocement was specified as JIS R 5214 by the Japan Industrial Standards. Table.1 shows a typical chemical composition of the Ecocement. The Ecocement is characterized by the large content of Al_2O_3 and Fe_2O_3, as well as a large content of SO_3 added to adjust the setting time. The Ecocement contains around 0.05% of Cl^-, approximately seven times as much chloride as normal Portland cement (hereafter, "normal cement" or "N") currently produced in Japan.

Table 2 shows mineral composition of the Ecocement. Although the Ecocement is similar to the normal cement in terms of mineral composition, it contains smaller amounts of C_3S and C_2S and larger amounts of C_3A and C_4AF, compared to the normal cement. As to the physical properties, fineness of the Ecocement is higher than that of the normal cement, allowing increase in the hydration activity. It is equal to N in terms of other properties.

Table 1. Chemical and compound compositions of cement

TYPE OF CEMENT	CHEMICAL COMPOSITION (%)									COMPOUND COMPOSITION (%)			
	IGN. LOSS	SIO_2	AL_2O_3	FE_2O_3	CAO	MGO	SO_3	R_2O	CL	C_3S	C_2S	C_3A	C_4AF
E	1.1	17.8	7.2	4.1	61.1	1.8	3.9	0.3	0.054	49	12	14	13
N	2.4	21.5	4.9	2.8	64.6	1.2	2.0	0.6	0.008	57	19	8	8

Table 2. Physical properties of cement.

TYPE OF CEMENT	DENSITY (g/cm^3)	FINENESS (cm^2/g)	SETTING			COMPRESSIVE STRENGTH (MPa)*		
			AMOUNT OF WATER (%)	INITIAL (H:M)	FINAL (H:M)	3 DAY	7 DAY	28 DAY
E	3.19	4130	31.2	2:40	4:10	28.8	36.3	51.2
N	3.15	3490	26.9	2:20	3:10	28.2	43.4	59.0

** Specimen with 50 mm in diameter and 100 mm in height.*

1.2 Ecocement plant

Figure 1 shows an Ecocement plant located in Chiba, Japan, which began its Ecocement production operation in 2001 for the first time in the world. The production ability is approximately 110 000 tons a year, and only normal Ecocement is produced at present. In addition to this Chiba plant, another Ecocement plant began operation in Tokyo in 2006, with an annual production capacity of 130 000 t of cement.

Figure 1. Ecocement plant under operation in Chiba, Japan.

2. OUTLINE OF THE MOLTEN SLAG GENERATED FROM MUNICIPAL WASTE

2.1 Outline of the municipal waste molten slag

The municipal waste molten slag is produced by crushing the solidified incinerated ash that has been melted at a high temperature. The molten slag used as the aggregate for the concrete is developed to reduce the incinerated ash, to achieve vitrification of leached-out heavy metals and to facilitate the recycling. The municipal waste molten slag is defined as "Melt-solidified slag aggregate for concrete derived from municipal solid waste and sewage sludge" by JIS A 5031 in 2006. JIS A 5031 specifies the content and leaching amount of toxic substances such as heavy metals, as well as the requirements for the molten slag used as concrete aggregate. Japan Concrete Products Association recommends that the acceptance test and toxic substance leaching test should be conducted when the molten slag is actually used.

2.2 Quality of the aggregate generated from the municipal waste molten slag

Table 3 shows a typical example of quality of the aggregate generated from the municipal waste molten slag. The JIS A 5031 criteria are also listed.

Table 3. Example of molten slag test (type: MS2.5).

ITEM			RESULT	CRITERIA
Leached-out toxic substances	**Cadmium**	**mg/L**	< 0.001	0.01 or less
	Lead	**mg/L**	< 0.005	0.01 or less
	Hexavalent chromium	**mg/L**	< 0.02	0.05 or less
	Arsenic	**mg/L**	< 0.002	0.01 or less
	Total mercury	**mg/L**	< 0.0005	0.0005 or less
	Selenium	**mg/L**	< 0.002	0.01 or less
	Fluorine	**mg/L**	0.2	0.8 or less
	Boron	**mg/L**	0.01	1 or less
Toxic substance content	**Cadmium**	**mg/kg**	< 1	150 or less
	Lead	**mg/kg**	17	150 or less
	Hexavalent chromium	**mg/kg**	< 1	250 or less
	Arsenic	**mg/kg**	< 0.5	150 or less
	Total mercury	**mg/kg**	< 0.03	15 or less
	Selenium	**mg/kg**	< 0.5	150 or less
	Fluorine	**mg/kg**	150	4000 or less
	Boron	**mg/kg**	14	4000 or less
	Density in saturated surface-dry condition	**g/cm^3**	2.75	2.45 or more
	Absorption ratio	**%**	1.61	3.0 or less
	Expansibility	**%**	< 0.2	Mortar expansibility is 2% or less
(Tamagawa Garbage Incinerator Plant, test result reported in Dec. 2006) *(Criteria are taken form JIS A5031)*				

3. QUALITY OF CONCRETE PAVING BLOCKS INCLUDING ECOCEMENT

3.1 Items to be determined

To use the Ecocement for the base concrete of the concrete paving blocks, the following three items were determined.

1. Development of concrete strength.
2. Plastic deformation quantity of blocks.
3. Effect of the concrete exposure time after mixing.

3.2 Development of concrete strength

3.2.1 Experiment design

Table 4 shows the experiment design conducted to determine the development of concrete strength.

Table 4. Experiment design for determining the development of concrete strength

ITEM	DESCRIPTION	REMARKS
Cement type	Normal Portland cement (N) Ecocement (E)	
Unit content of cement (kg/m^3)	316, 366, 416	
Unit content of water	Four levels	Selected so that the fill factor should be between 88 and 94%.

3.2.2 Experimental procedure

Below is the outline of the experiment procedure.

1. Concrete paving blocks of 98 × 198 × 60 mm are used as specimens.
2. Vibration time for compacting is set to 5 seconds for all specimens.
3. Concrete fill factor was calculated using the following equation.

Fill factor (%) = (Block mass per unit volume/ Concrete theoretical mass per unit volume, given that there is no void) x 100

4. Primary curing was performed with the maximum temperature of 27°C and the retention time of 15 hours.
5. The secondary curing was performed indoors for 13 days.
6. The strength test was performed with the span of 160 mm and the load at center.
7. Plastic deformation was determined by obtaining the mean value of block widths measured at the two points and its difference from the frame width.

3.2.3 Effect of the Ecocement on the unit content of water

Figures 1 and 2 show the relations between the unit content of water and the fill factor in the cements N and E. The fill factor of each cement increases with the unit content of water. The more the unit content of water volume is larger, the larger the fill factor increases.

Figure 3 shows the relation between the unit content of water and the fill factor of each cement (each fill factor used is the average fill factor obtained from the three levels of unit content of cement). From the figures, it is clear that, compared to the cement N, the Ecocement requires approx. 5 kg/m^3 larger unit content of water to obtain the same fill factor with the cement N.

3.2.4 Development of concrete strength

Figure 4 and 5 show the relation between the fill factor and the flexural strength of the cements N and E. The flexural strength of each cement increases linearly with the fill factor. The more the unit content of cement volume is larger, the larger the flexural strength increases.

It is known that the strength of the concrete produced using the dry-cast process can be expressed by a linear expression using the water-cement ratio and fill factor as variables. Thus, the multiple regression equation shown in Table 5 was used to estimate the flexural strength (Y) using the water-cement ratio (X1) and fill factor (X2) as independent variables.

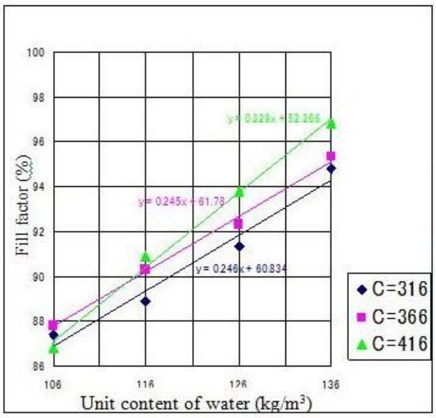


Figure 1. Normal cement fill factor.

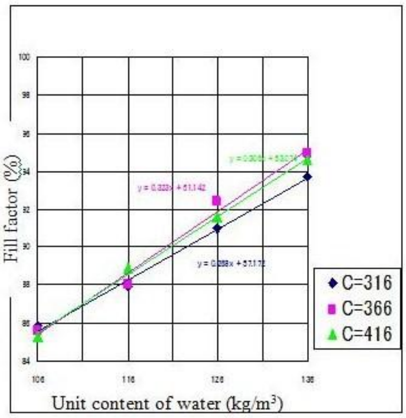


Figure 2. Ecocement fill factor.

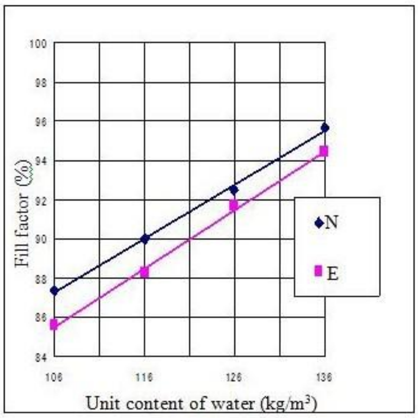


Figure 3. Comparison of fill factors.

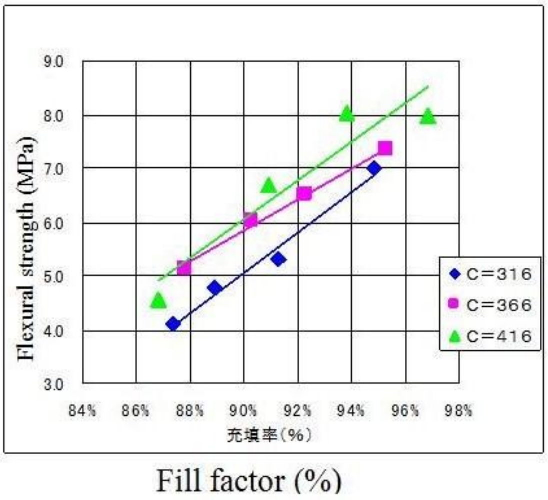


Figure 4. Fill factor and flexural strength (Cement N).

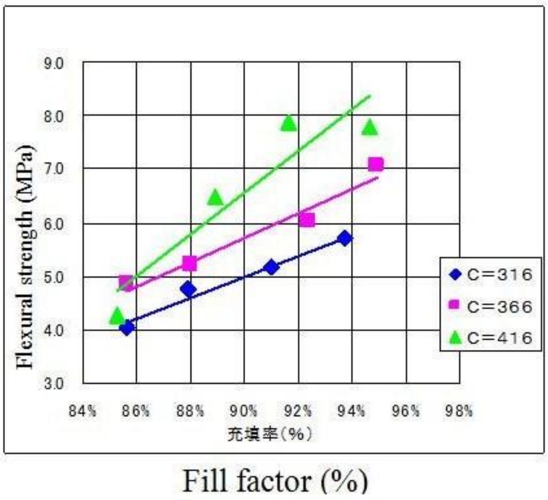


Figure 5. Fill factor and flexural strength (Cement E).

Table 5. Multiple regression equation used to estimate the flexural strength.

CEMENT TYPE	MULTIPLE REGRESSION EQUATION
N	$Y = 1.06X_1 + 0.44X_2 - 37.53$ ($R^2 = 0.94$)
E	$Y = 1.63X_1 + 0.41X_2 - 36.29$ ($R^2 = 0.85$)

3.2.5 Estimation of unit content of cement

The unit content of cement for the Ecocement shown in Table 6 was estimated by using the multiple regression equation obtained in 4.2.4 above, the fill factor at the plant and the result of unit content of water. When the Ecocement was used, an increase in the unit content of cement by 2 kg/m^3 was observed. This result shows that the Ecocement is capable to obtain the desired strength when it has the unit content of cement nearly the same amount as for the cement N.

For the concrete having high fluidity, it has been reported that the Ecocement strength is lower than that of the cement N by around 10%. For the concrete having low fluidity, the Ecocement did not show such drawback.

Table 6. Ecocement estimates.

CEMENT TYPE	DESIRED VALUE OF FLEXURAL STRENGTH (Y), (MPa)	RESULT OF FILL FACTOR (X_2), (%)	RESULT OF UNIT CONTENT OF WATER (W), (kg/m^3)	ESTIMATE OF UNIT CONTENT OF CEMENT (C), (kg/m^3)
N	6.10 or more	92.0 or more	116	345
E			121	347
Increase in unit content of cement when E is used				+2

3.3 Plastic deformation quantity of blocks

Figure 6 and 7 show the relation between the unit content of water and the plastic deformation quantity in the cements N and E.

The plastic deformation of cement N sharply increases when the unit content of water is increased to 136 kg/m^2. On the other hand, the Ecocement does not show little plastic deformation, as far as the experiment is concerned. This indicates that the Ecocement has the advantage over the cement N in terms of dimensional accuracy.

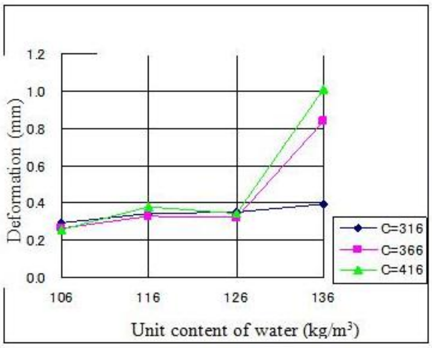


Figure 6. Plastic deformation of cement N.

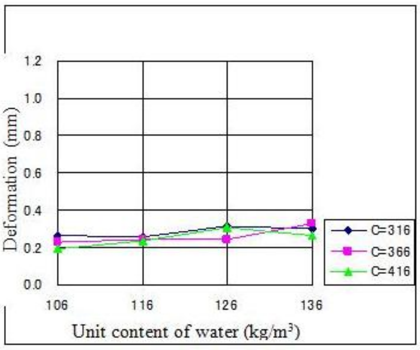


Figure 7. Plastic deformation of cement E.

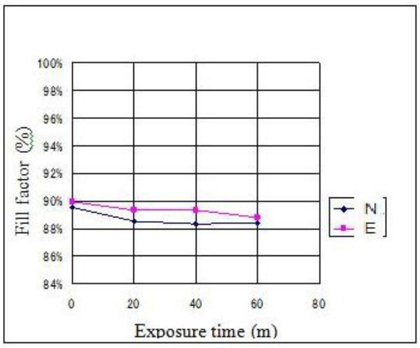


Figure 8. Changes in fill factor with the exposure time.

3.4 Effect of the exposure time after mixing

It is not possible to obtain a stable fill factor once the concrete is mixed, as its hydration process continues. This is more prominent when the concrete temperature becomes higher. To obtain blocks with a fixed quality, it is desirable for the concrete to have less influence from exposure time after mixing. The effect of the exposure time after mixing on the Ecocement was determined.

Figure 8 shows the changes in the fill factor of each cement with different exposure times. Under the conditions of this experiment with the concrete temperature of 9°C, the fill factor did not decrease much after the 60 minute exposure time. Also, there was no significant difference between the cements E and N when the concrete temperature was increased in the subsequent experiment.

3.5 Result

1. For the zero-slump concrete, the strength development of the cement E is almost equal to that of the cement N, and thus it is not necessary to increase the unit content of cement of the cement E.
2. The plastic deformation of the cement E is slightly smaller than that of the cement N, and thus the Ecocement has the advantage over the normal cement to obtain the dimensional accuracy.
3. The influence of the exposure time after mixing on the Ecocement fill factor was equal to that of the normal cement.

4. DEVELOPMENT OF CONCRETE PAVING BLOCK USING MOLTEN SLAG

4.1 Selecting the appropriate molten slag

In selecting the molten slag, two factors were considered: the working environment of the block producing plant and the safety of the site while the blocks are in-service.

There are types of molten slags that contain toxic substances such as the toxic heavy metals, and they pose a threat to the health of people working in the production plant if such toxic heavy metals are stored in large quantities there. Also, leaching of toxic heavy metals from the block construction sites must be avoided as it would pollute the environment.

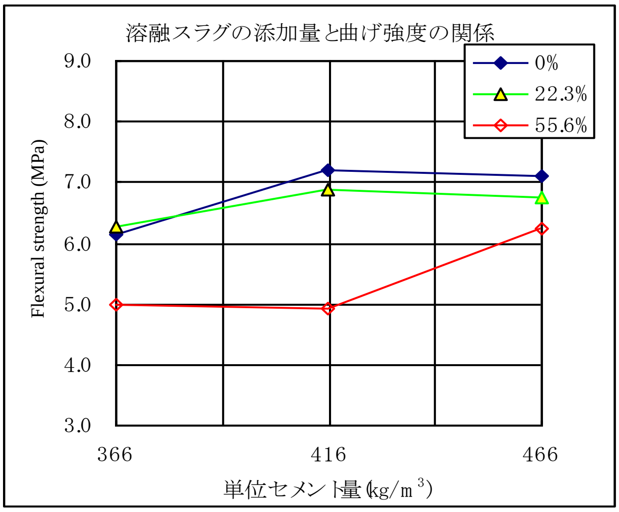
For this reason, the molten slag produced by the Tamagawa Garbage Incinerator Plant was selected, on condition that it meets the requirements for the JIS A 5031 quality standard. The molten slag produced by the plant meets almost all JIS standards.

4.2 Quality of concrete paving blocks

The target volume of the molten slag was set to 50% of the concrete weight, and an optimal mix proportion was determined. There is a concern that using the molten slag decreases the strength. Therefore, the unit content of cement was increased from 366 kg/m^3 to 466 kg/m^3 in 50kg/m^3 increments.

Figure 9 shows that the relation between the unit content of cement and the flexural strength when the molten slag content is set to 22.6% or 55.6%. As it is apparent from the figure, when the molten slag is added by 22.3%, the flexural strength was closed to that of 0%. The strength was lowered by 1 N/mm^2 to 2 N/mm^2 when the molten slag added was 55.6%. However, even with the 55.6% molten slag, the same level of strength as the original mix (no molten slag; the unit content of cement, 366 kg/m^3) was able to obtain when the unit content of cement was increased by 100 kg/m^3 to be 466 kg/m^3. There is an alternate way of eliminating the strength degradation due to the molten slag, which uses a high-performance water reducing agent.

It was confirmed that specimens meet the dimensional accuracy and skid resistance of the criteria specified for the concrete paving blocks. The Ecocement was used for the base concrete.



Unit content of water (kg/m^3)

Unit content of cement (kg/m^3)

Figure 9 Relation between the molten slag content and the flexural strength.

Table 7. Quality standard for the concete paving blocks.

ITEM	STANDARD VALUE
Flexural strength	5.0 MPa or more
Dimensional accuracy	Within ± 2.5 mm
Skid resistance	Walkway: 40 BPN or more, Road: 60 BPN or more.

4.3 Durability of concrete paving blocks

There has been a report that the concrete using the molten slag has poor freeze-thaw resistance. To verify this, a test of freeze-thaw resistance of concrete paving block was conducted in accordance with ASTM C67. The concrete mix proportion was modified to improve the mass loss after 50 cycles. The concrete blocks satisfied the mass loss criteria of 1.0% or less and showed no visible change such as cracking. As a result, it was ensured that the concrete paving blocks have sufficient durability against freeze-thaw.

4.4 Evaluating the effect on the surrounding environment

Table 8. Result of the block leaching test.

ITEM			RESULT	CRITERIA
Leached-out toxic substances	**Cadmium**	**mg/L**	< 0.005	0.01 or less
	Lead	**mg/L**	< 0.01	0.01 or less
	Hexavalent chromium	**mg/L**	< 0.02	0.05 or less
	Arsenic	**mg/L**	< 0.002	0.01 or less
	Total mercury	**mg/L**	< 0.0005	0.0005 or less
	Selenium	**mg/L**	< 0.002	0.01 or less
	Fluorine	**mg/L**	0.4	0.8 or less
	Boron	**mg/L**	0.05	1 or less
(Criteria are specified by Soil Contamination Countermeasures Act). *(The test method is according to the Tank Leaching method specified by the Concrete Committee of Japan Society of Civil Engineers).*				

To prevent the toxic substances in the concrete block from leaching into the surrounding environment, leaching tests were conducted to determine if the block meets the environmental criteria specified by the country. Table 8 shows the results of the leached-out heavy metals. For this test, the blocks were not crushed but used as-are.

The quantity of leached-out toxic substances meets the environmental criteria for the soil contamination specified by the country.

4.5 Determination of concrete paving block recyclability

In many cases, no longer needed concrete paving blocks are removed from the paving to be reused. They will end up being processed as crusher run for a base course. Hence, a further leaching test was required to ensure that the pulverized block also meets the environmental criteria specified by the country. Since it is possible that the hexavalent chromium leaches from the molten slag, a reducing agent (ferrous sulfate) was added. From the test results shown in Table 9 (test on toxic substance content) and Table 10 (test on leaching after pulverization), it is clear that the concrete paving blocks meet the environmental criteria specified by the country.

Table 9 Result of the test on block toxic substance content

ITEM			RESULT	CRITERIA
Toxic substance content	**Cadmium**	**mg/kg**	< 10	150 or less
	Lead	**mg/kg**	21 to 22	150 or less
	Hexavalent chromium	**mg/kg**	< 10	250 or less
	Arsenic	**mg/kg**	< 10	150 or less
	Total mercury	**mg/kg**	< 1	15 or less
	Selenium	**mg/kg**	< 10	150 or less
	Fluorine	**mg/kg**	110 to 133	4000 or less
	Boron	**mg/kg**	< 100	4000 or less
(Criteria for content are specified by Soil Contamination Countermeasures Act) *(The test method is according to JIS K0058-2)*				

Table 10 Result of the test on leaching after pulverization.

ITEM			RESULT	CRITERIA
Leached-out toxic substances	**Cadmium**	**mg/L**	< 0.005	0.01 or less
	Lead	**mg/L**	< 0.01	0.01 or less
	Hexavalent chromium	**mg/L**	0.03	0.05 or less
	Arsenic	**mg/L**	< 0.002	0.01 or less
	Total mercury	**mg/L**	< 0.0005	0.0005 or less
	Selenium	**mg/L**	< 0.002	0.01 or less
	Fluorine	**mg/L**	< 0.4	0.8 or less
	Boron	**mg/L**	< 0.05	1 or less
(Criteria are specified by Soil Contamination Countermeasures Act). (The test method is according to JIS K0058-1)				

5. CONCLUSION

1. The Ecocement, like the normal cement, can be used as a material in the concrete paving block.
2. By adopting an appropriate mix and controlling system, the Ecocement can be safely used even when the amount of municipal waste molten slag used exceeds 50% of the block weight.
3. One ton or more of the municipal waste can be recycled into the concrete paving blocks per square meter of 60 mm block. That is to say, the municipal waste incinerated ash, which used to be dispensed of, can be now recycled more safely and more beneficially while contributing to build a sustainable community.

6. REFERENCE

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