Goumans/Senden/van der Sloot, Editors
Waste Materials in Construction: Putting Theory into Practice

Producing Permeable Blocks and Pavement Bricks from Molten Slag

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Abstract

Studies of the technology of melting and solidifying are underway as a means of detoxification and volume-reduction of municipal solid waste incineration residue. The molten slag does not leach heavy metals, and can be used as concrete gravel and roadbed aggregate. We have produced water-permeable blocks from slags made by a surface-melting melting furnace and a plasma-melting furnace. Also, we have fabricated and installed pavement bricks using slag from a commercial surface-melting furnace.

Both attempts have been successful, as the end results satisfied the required product standards, and showed no heavy-metal leaching.

1. Introduction

The treatment and disposal of municipal solid waste (MSW) come under the jurisdiction of the municipality where it is generated, and it is the common practice to incinerate the waste and landfill the subsequent residue. However, acquiring suitable sites for landfilling is becoming more difficult every year, and the reduction of waste itself as well as the volume destined for landfill, has become an urgent issue. As new regulations controlling waste disposal methods and recycling are issued, vast efforts are made in recycling wastes and developing means of effective re-use of the residues.

A new technology has been developed by which the residue is melted at a high temperature and the molten ash is turned into slag by quenching, reducing the waste volume and detoxifying simultaneously. There are 16 melting facilities in operation today, and experiments are underway to utilize the slag coming from these plants. A standard specification for its application is being prepared for the promotion of its use.

Due to its characteristics, use of slag is mainly concentrated in the areas of roadbed materials and concrete aggregates. In this article, we report the test results of making water-permeable blocks made of slag coming from two different systems of melting, and also the results of fabricating and installing pavement bricks made from slag produced by a commercial melting plant.

2 Melting Systems

The methods of melting incineration residue can be divided roughly into two major categories, fuel-burning system and electric melting system. Takuma has already built seven operational facilities in the fuel-burning category, which are Reflective Surface-Melting Furnaces. In the electric melting system, Takuma is currently developing and experimenting Graphite-Electrode

Plasma Melting Furnace. Both types of melting furnaces are installed adjacent to MSW incineration plants. The residual ash is first processed by magnetic separator and sorted according to the particle size before going into the melting furnace. The slag is either quenched in water, or air-cooled gradually.

Figure 1 shows the incineration residue melting system.

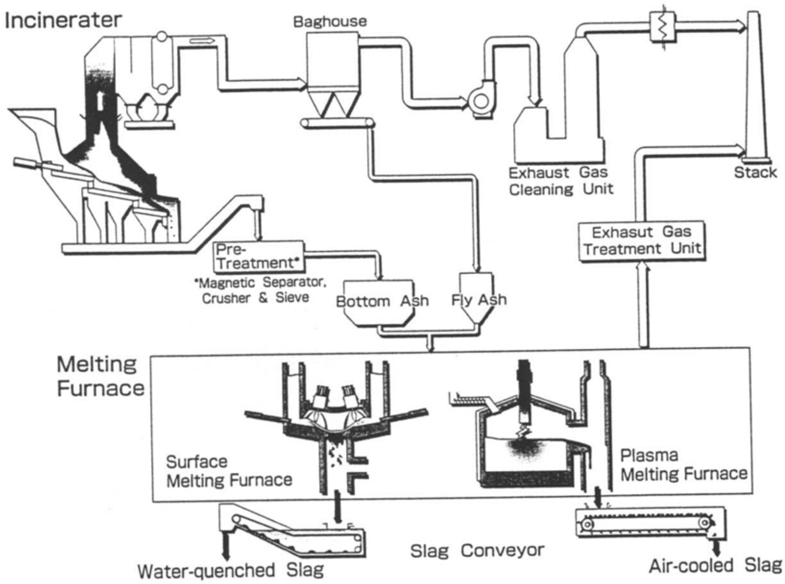


Figure 1 Refuse Incineration Residue Melting System

2.1. Surface-melting Furnace

Figure 2 illustrates the structure of a surface-melting furnace. The ash which was stored in the ash storage bin is fed into the furnace by the ash extruder. It forms a melting slope at roughly the equilibrium pitch of the ash. Burners pointing approximately perpendicular to such slopes are installed on the roof of the furnace.

The ash is melted from its surface by the heat of these burners and the radiant heat from the refractory materials of the roof. The molten slag flows down along the melting slopes which are located diametrically around the slag tap at the center of the furnace.

The slag flows further down along with the combustion gas into the quenching bath, and chilled quickly, it turns into black

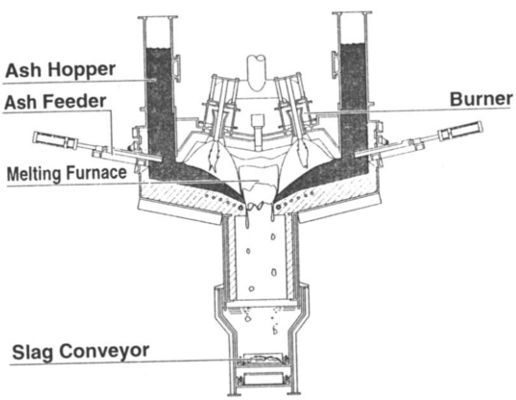


Figure 2 Surface-melting Furnace

granular slag.

The furnace exterior is cooled by the water jacket, and its inner wall consists of refractory materials of superior heat and erosion resistance.

2.2. Plasma Melting Furnace

Figure 3 shows the schematics of plasma melting furnace. It is lined with refractory materials which are protected on the lid and side walls by water jackets. The bottom has air-cooling box that protects its refractory linings.

The incineration residue is fed into the furnace at a pre-determined quantity by means of a screw feeder. It is melted into slag by the conductive heat from the high-temperature plasma arc. It then overflows through the slag tap continuously.

The exhaust gas from the melting furnace goes out through the slag tap where the unburnt gas generated by the melting process is burnt, preventing the molten slag discharge from cooling and solidifying.

Most metal contents in incineration residue such as iron and copper are reduced during melting, and accumulate at the bottom of the furnace due to their higher specific gravity. They are discharged periodically by opening the tap hole located at the bottom of the furnace.

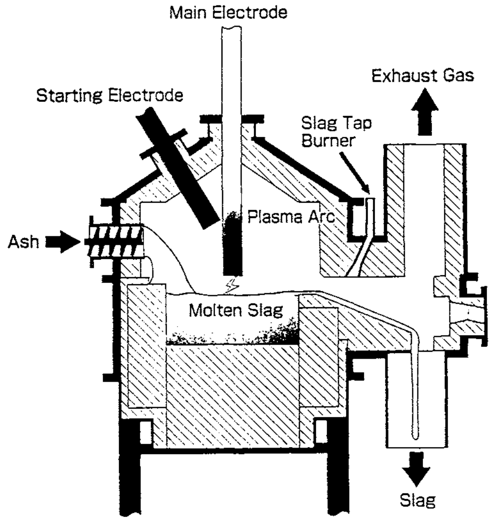


Figure 3 Plasma Melting Furnace

3. The Characteristics of Molten Slag

We have melted bottom ash and fly ash from a stoker-type incinerator using various surface-melting furnaces and plasma furnaces of 5t/day capacity, and obtained data on slag characteristics.

The bottom ash was wet, and it came through 30mm mesh, then de-watered down to 5% moisture. Its ferrous content was removed by the magnetic separator. The fly ash came solidified with cement, and was tested as it was.

Tests were carried out using (1) bottom ash alone, and (2) a combination of three parts bottom and one part fly ash.

3.1. Analysis

Table 1 shows the results of analysis of the slags

The main ingredients of the slag are SiO_2. Al_2O_3 and CaO. While surface-melting is done in an oxidizing atmosphere, it is in a reducing atmosphere with the plasma-melting furnace. Therefore, Fe_2O_3 is reduced into metallic iron in the plasma furnace, decreasing the iron content in the slag. This also gives more grayish tinge to the slag.

The same can be said about other metals.

Table 1 Result of Analysis of the Slags

Item	Unit	Surface-Melting Furnace Bottom Ash Slag	Surface-Melting Furnace Mixed Ash Slag*	Plasma Melting Furnace Bottom Ash Slag	Plasma Melting Furnace Mixed Ash Slag*
SiO_2	%	39.0	37.5	43.3	41.4
TiO_2	%	1.3	1.1	1.2	1.2
Al_2O_3	%	23.3	23.9	28.7	26.0
Fe_2O_3	%	10.2	9.2	2.9	2.9
CaO	%	19.2	22.3	18.9	24.0
MgO	%	2.9	2.7	3.0	2.8
K_2O	%	1.1	0.8	1.0	0.4
Na_2O	%	3.9	3.0	3.8	2.5
P_2O_5	%	2.4	2.3	0.9	1.0
Softening Point	°C	1,170	1,200	1,200	1,220
Melting Point	°C	1,180	1,200	1,210	1,230
Flowing Point	°C	1,200	1,220	1,280	1,260

*Mixing Ratio: Bottom Ash : Fly Ash = 3 : 1

Table 2 Physical Test Result of the Slag

Melting Furnace		Surface Melting Furnace				Plasma Melting Furnace		
No.		F1-L	F1-S	F2-L	F2-S	P1-L	P1-S	P2-S
Specimen Bottom Ash	%	100	100	75	75	100	100	75
Fly Ash	%	0	0	25	25	0	0	25
Particles Clearing: 53 mm Mesh Size	%	100.0		100.0				
37.5mm	%	94.9		96.1				
31.5	%	93.0		94.5				
26.5	%	90.1		93.8		100.0		
19	%	87.4		91.7		97.7		
13.2	%	84.1		90.0		94.2		
9.5	%	82.4	100.0	88.5	100.0	91.9	100.0	100.0
4.75	%	75.3	94.6	83.9	88.2	83.3	94.2	95.1
2.36	%	55.1	77.8	64.2	64.5	69.3	74.5	60.1
1.18	%	25.7	38.3	28.7	29.2	33.3	28.5	25.6
600 μm	%	8.1	14.1	8.7	7.8	13.5	14.8	7.15
300	%	3.8	6.51	3.0	3.4	6.2	3.3	2.9
150	%	1.9	2.94	1.2	1.4	2.8	2.0	1.5
Specific Gravity Saturated, Dry Surface	–	2.064	2.744	2.294	2.657	2.423	2.644	2.665
Bulk Specific Gravity	–	1.876	2.718	2.138	2.584	2.251	2.601	2.619
Apparent S.G.	–	2.307	2.793	2.534	2.787	2.720	2.718	2.746
Water Absorption Rate	%	9.958	0.990	7.306	2.801	7.644	1.661	1.774
Friction Loss	%	70.6	17.0	64.1	15.4	61.1	16.2	14.7
Stability	%	23.9	6.4	27.3	8.0	17.6	4.8	10.7
Wash Loss	%	1.8	1.3	1.0	1.0	1.6	1.5	1.7
Weight/Volume	kg/l	1.426	1.540	1.489	1.516	1.441	1.548	1.582
Solid Volume Ratio	%	75.4	58.7	69.7	58.7	63.7	59.5	60.4
Optimum Compression Moisture	%	15.0	15.0	10.6	10.6	11.7	11.7	11.0
Maximum Dry Density	g/cm^3	1.801	1.801	1.860	1.860	1.692	1.692	1.786
Modified CBR	%	29.4	29.4	29.5	29.5	22.7	22.7	25.9
Liquid/Plastic Limit	%	NP	NP	NP	NP	NP	NP	NP

3.2 Results of the Physical Tests

Table 2 shows the results of physical tests of the slag. The letter 'L' in the table represents the results of tests according to the coarse aggregates standard (particle size distribution:10~40mm) whereas the letter 'S' indicates the results according to the fine aggregates standard (particle distribution:0~10mm). The latter slag was shifted through 10mm mesh.

The average particle sizes for surface-melt slag and plasma slag are both within the range of 1~1.5mm, but surface-melt slag has larger portion of coarse particles.

Water-quenched slag is glassy, which, if containing coarse particles of more than 10mm, is fragile, and is inferior in water-absorption, friction loss and stability. It does not meet the specification of coarse aggregate.

Once coarse particles over 10mm are removed, the test results in each item are improved. The particle size distribution indicates higher percentage of 5~2.5mm particles and lower percentage of 1mm and smaller particles. This water-quenched slag can be crushed, and its particle distribution can be adjusted to satisfy the specification for fine aggregate.

Its modified CBR value is between 20% and 30%, but it can be used as road aggregate without ill effect when mixed with other roadbed materials available commercially.

3.3 Safety

The result of leaching test, as the prime safety benchmark for the slag, shows that the leachings of heavy metals are within the guideline, and satisfies the soil standards specified by the publication No13 and No46 of the environmental agency.

4. Producing Water-Permeable Blocks

The results of producing water-permeable blocks (size: 200mm×100mm×60mm) are described below. As mentioned earlier, bottom ash by itself, and its mixture with fly ash, were used in surface-melting furnace and plasma furnace,

4.1 Method of Manufacturing

Figure 4 shows the manufacturing process of the water-permeable blocks.

The slag went through mesh size 5mm, and the iron content that causes bubbling is removed by the magnetic separator. Two kinds of blocks were made, one with a single layer of slag, and another with two layers, the surface layer being added for appearance using shard. Table 3 shows the mixing ratio for the components of these blocks.

The base layer consists of slag and sintering accelerator that sinters the slag at temperatures below the melting point of the slag, at the ratio of 91:9. Water solution of CMC(an organic binder) was added for molding.

Since the slag from the surface-melting furnace showed melting point about 30° to 50°C lower than that of slag coming from plasma furnace, the sintering temperature was kept lower than the melting point. The period of sintering for the slag from surface-melting furnace is kept at 15 hours of rising temperature, 2 hours maintaining at 900°C, while they are 17 hours, and 2 hours at 1000°C, respectively.

4.2 The Result of Production

The results of various physical tests of sintered water-permeable blocks are listed in Table 4.

The permeation index for both types satisfies 0.01cm/sec defined by the Interlocking Association Specification. On average, single-layer block turns out 0.046cm/sec whereas two-

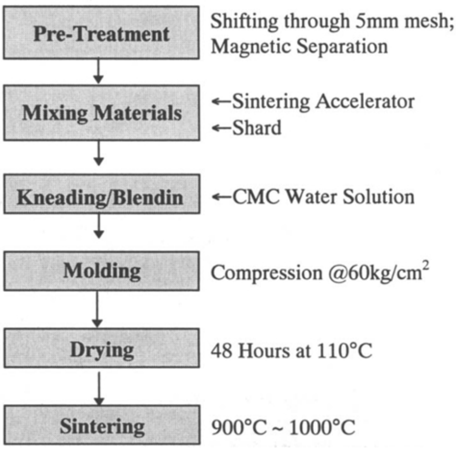
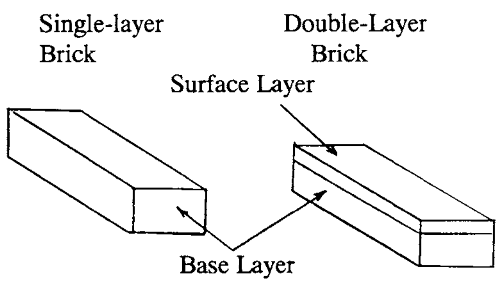


Figure 4 Production Process of Water Permeating Blocks

Table 3 Mixing Ratio

Raw Material		Ratio(%)
Base Layer	Slag	91.0
	Accelerator	9.0
Surface Layer	Slag	45.5
	Shard	45.5
	Accelerator	9.0



layer block betters it by 37% at 0.063cm/sec. This is attributed to the fact that the permeability of the shard is so high that the difference comes from the base layer. Relative bending strength is lower with the two-layer block that can be presumed as caused by the low affinity between the base and top layers.

The heavy metals leaching test proved that it is within the soil standard specified by the Publication No13,No46 of the Environmental Agency.

Table 4 Physical Test Results of Water-Permeable Blocks

Furnace		Surface-Melting Furnace				Plasma Melting Furnace				ILB Spec.
Material		Bottom Ash		Bottom Ash + Fly Ash		Bottom Ash		Bottom Ash + Fly Ash		Value
Layer		1	2	1	2	1	2	1	2	
Molded Density	g/cm^3	1.88	1.80	1.90	1.87	1.86	1.81	1.89	1.85	–
Sintered Density	g/cm^3	1.90	1.81	1.94	1.90	1.90	1.85	1.88	1.83	–
Shrinkage- Length	%	0.54	0.39	0.58	0.48	0.73	0.72	0.05	0.11	–
- Width	%	0.55	0.47	0.68	0.68	0.87	0.89	0.13	0.34	∓
- Height	%	0.19	0.25	1.00	1.29	1.13	1.49	–0.21	–0.01	–
Permeation Index	cm/se	0.038	0.051	0.042	0.065	0.061	0.082	0.039	0.052	0.01
Bending Strength	kgf/c	46.7	40.4	51.7	57.1	38.3	32.0	40.2	35.0	30
Compression	kgf/c	184.7	278.3	300.0	321.6	474.3	521.1	319.5	274.1	170

4.3 X-ray Diffraction of Water-Permeable Block

In order to determine the mineral composition of the product, X-ray diffraction was done, and diffraction values are calculated to show their mineral composition, as shown in Table 5.

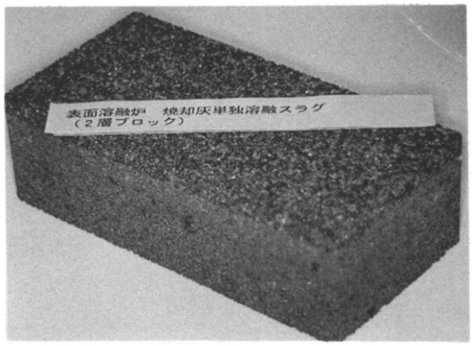
It reveals that the main components are SiO_2, Al_2O_3 and CaO, causing gehlenite and anorthite to precipitate, and also more augite precipitated in the surface-melting slag block than that of plasma furnace slag, due to the influence of iron. The exterior view of water-permeable block is shown in Photograph 1.

Table 5 Mineral Composition of Water-Permeable Blocks

Furnace	Surface Melting		Plasma Melting	
Materials	Bottom Ash	Bottom Ash + Fly Ash	Bottom Ash	Bottom Ash +Fly Ash
	1-Layer Block	2-Layer Block	1-Layer Block	2-Layer Block
Gehlenite	+	+++	+++	+++
Anorthite	+	+	++	++
Augite	+++	+++	+	+
Wollastonite		•		

Precipitation +++>++>+>•

1. Gehlenite : $2CaO.Al_2O_3.SiO_2$
2. Anorthite : $CaO.Al_2O_3.2SiO_2$
3. Augite : $Ca(Mg,Fe)Si_2O_6$
4. Wollastonite : $CaO.SiO_2$



Photograph 1 Water-Permeable Block

5. Production of Pavement Brick

We produced approximately 11,000 pieces of pavement brick using slag from a surface-melting furnace we installed. The bricks were used to pave the footpath in our new head office premises, covering roughly 240 m^2.

5.1 Preliminary Testing

Before the production, a preliminary test was conducted. The sintering was to be done using ordinary tunnel kiln. Sintering temperature was set within the 1200~1230°C range, and the suitable material mix and the granular sizes were determined accordingly.

Small test lots of 2 tons were formed and sintered in order to locate problem areas. The following discoveries were made.

(1) Slag size was to be limited to 1.0mm and smaller, and the slag ratio was set at 20%.

(2) Sintering was done of shelves, and multiple layers were sintered to the extent that no deformation occurred.

(3) Sintering Temperature was set at 1200~1230°C.

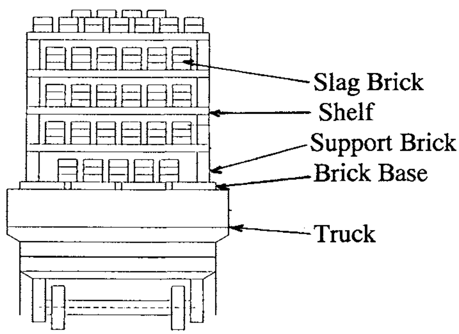


Figure 5 Brick Sintering Shelf Assembly

(4) The color variance of the product was such that the top layer became dark while the bottom layer did not get sufficient sintering, and turned grayish. This was avoided by placing bricks with larger spacing. (Refer to Figure 5 Brick Placement on Sintering Shelves)

(5) For coloring, 2% of chromite pigment was added after checking the relationship between the amount of pigment and product coloring.

5.2 Production Process

Figure 6 shows the production process of pavement bricks.

After having its ferrous metals removed by the magnetic separator, the slag was crushed, and went through 1.0mm sieve. The recovery rate was approximately 95%.

The brick material ratio was: Slag(1.0mm<): Grog (3.0mm<): Ceramic Gravel (1.0mm<): Clay (1.0mm<) at 20 : 35 : 25 : 20. To this mixture, 2% of pigment were added. Kneading and blending was done by a Müller mixer for 15 minutes. Molding was done by a 200 ton friction press, and the bricks were loaded onto the sintering truck.

Drying for about 48 hours at 80 ~ 150°C was followed by the sintering process in a tunnel kiln for about 80 hours at 1200°C~1230°C.

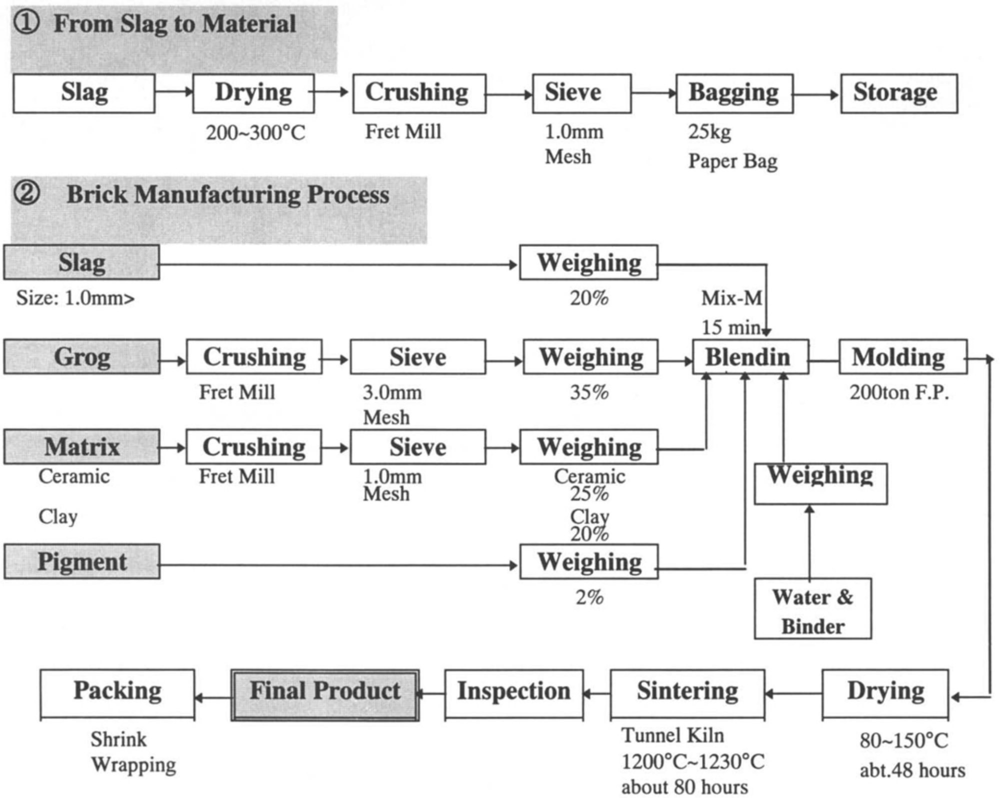


Figure 6 Pavement Brick Manufacturing Process

5.3. Quality of the Products

(1) Color

The color is brownish, with delicate variances due to the location of the brick on the truck as it received different temperatures and oxygen of varied densities. Black dots appear on the surface caused by the oxides of metals remaining in the slag. Photograph 1 displays the appearance of the bricks as they are laid own on the floor.

Photograph 2 Pavement Brick

Photograph 3 Pavement Brick

(2) Quality

Table 6 shows the physical properties.

These are the average values derived from 10 samples drawn at random from the products.

The water absorption ratio at 4.1% and the compression strength at 1,278kg/m^2 meet the JIS standard of <13% and >200kg/m^2, respectively.

Table 6 Physical Properties of Pavement Brick

Item		Unit	Averag e	Standard Deviation	JIS R 1250 Standard Brick No.3	Ordinary Pavement Brick
Apparent Pore Ratio		%	9.4	1.06	-	-
Water Absorption Rate		%	4.1	0.5	less than 13	-
Apparent Specific Gravity		-	2.5	0.027	-	2.35
Bulk Specific Gravity		-	2.26	0.018	-	2.29
Compression Strength		kg/cm^2	1,278	128.1	more than 200	-
Bending Strength		kg/cm^2	134	21.7	-	-
Measurement	Length	mm	226.5	0.78	Standard Size	230 mm
	Width	mm	112.5	0.58	Standard Size	114 mm

(3) Leaching Test

In order to determine the safety of the brick, elution tests have been carried out.

The test specimens were bricks crushed to sizes smaller than 5mm, and the whole bricks. The three test methods were: Publication No13,No46 of the Environmental Agency and Low pH Method(controlled to pH4 using HNO_3).

Table 7 shows the leaching test results.

Table 7 Leaching Test Results of Pavement Bricks

Specimen		Crushed			Whole			Environm-ental Soil Standard
Item	Unit	No13	No46	pH4(HNO_3)	No13	No46	pH4(HNO_3)	
pH		7.3	7.8	4.1	6.4	6.4	4.2	–
R-Hg	mg/l	–	<0.0005	<0.0005	–	<0.0005	<0.0005	None
T-Hg	mg/l	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Cd	mg/l	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Pb	mg/l	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
O–P	mg/l	–	<0.02	<0.02	–	<0.02	<0.02	None
Cr^{6+}	mg/l	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
As	mg/l	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.01
T-CN	mg/l	–	<0.02	<0.02	–	<0.02	<0.02	None
PCB	mg/l	–	<0.0005	<0.0005	–	<0.0005	<0.0005	None
Se	mg/l	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.01
Cl	mg/l	0.2	0.6	1.2	0.9	1.4	0.8	–

6. Conclusion

With this report, we have covered the examples of effective re-use of incineration residue slag. Further study on the control, disposal and re-use of this material should be undertaken by the industry as well as the governments, as it is the key to the realization of resource-recycling society.