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Research and Development of Direct Melting Process for Municipal Solid Waste

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Abstract:

In Japan, the shortage of landfills for final disposal of residue from the incineration of municipal solid waste (MSW) continues to plague many local gorvernments. To prolong the life of existing landfills, various processes have been studied for reducing the generation and volume of MSW, and some have been already put to practical use. Nippon Steel built the first MSW direct melting furnace in 1979 and has since accumulated operating experience with the furnace over a long period. The direct melting process can not only solve the problem of landfill site shortage but also recycle MSW. To enhance its public acceptance, the process was improved to reduce the consumption of auxiliary feed materials. The improved process was demonstrated with a 50-t/d commercial melting furnace and confirmed to be capable of halving the consumption of coke and oxygen.

1. Introduction

Japan generates about 50 million tons of municipal solid waste (MSW) per year. About 74% of the MSW is incinerated to reduce its volume to about 16%, and the residue is dumped in landfills[1]. Some 15% of MSW is directly dumped without being incinerated. This means that 15 million tons (31%) of MSW per year is transported to landfills for ultimate disposal annually. The residual life of final disposal landfills as determined by dividing the remaining capacity of landfills (1.54 million cubic meters in 1996) by the volume of the MSW to be disposed of per year. This figure has been hovering below 10 years for the past few years. The lack of landfill sites for final disposal of MSW continues to be severe. The remaining surplus landfill capacities have diminished or plateaued in the past few years. This fact attests to the difficulty of constructing new landfills.

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The process whereby MSW is directly melted is reviewed as a drastic solution to the problem of landfill site shortage. Nippon Steel built the first coke-bed type MSW direct melting furnace in 1979. This melting furnace is still operating satisfactorily. The direct melting process converts MSW into useful materials such as slag. It can solve the landfill site shortage problem by one stroke and dramatically change a conventional incineration plant with the sole function of waste volume reduction into a resource recycling plant.

With the landfill site shortage problem increasing in severity, Nippon Steel researched and developed an improved process for reducing auxiliary feed material consumption as one precondition to accomplish for the popularization of the MSW direct melting furnace. In 1994, Nippon Steel's R&D to improve the process with a 10-t/d pilot furnace was completed[2].

Based on the 10-t/d furnace test results, a full-scale demonstration test was started in 1995, as required for the design of a commercial furnace. The results of the demonstration test are reported here. Research to improve the demonstration furnace continues. This paper outlines the demonstration test, describes the reduction in the consumption of auxiliary feed materials, and reviews the utilization of slag and iron (referred to as metal hereinafter).

2. Nippon Steel Coke-Bed Melting Furnace

2.1 Comparison of MSW disposal processes in final disposal volume

Three representative MSW disposal processes shown in **Fig. 1** are compared in terms of volume of residue to be dumped in landfills. Each process was based on the disposal of 100 tons of MSW. The proportions of combustible and noncombustible constituents in the MSW were put at 85% and 15%, respectively.

With incineration process A, the incinerator can handle the combustible constituent alone or MSW not containing noncombustible materials or those unfit for incineration. This means that the noncombustible waste must be added to the incineration residue and fly ash from the incinerator as materials for landfill.

The direct melting process C can melt both the combustible and noncombustible components at the same time. Slag, metal, and other molten matter from the melting furnace can be effectively utilized as resources. The only material for disposal is a small amount of fly ash.

The incineration-plus-incineration residue melting process B, which has come into practical use recently, has a lower landfill load than incineration process A because the incineration residue is recycled. Since the noncombustible constituents are difficult to melt, however, this process falls between the processes A and C in terms of the volume of material to be disposed. The coke-bed incineration residue melting process[3] can melt the noncombustible constituents together with the incineration residue, so that the landfill load is equivalent to that of process C.

As discussed above, the landfill load of the direct melting process is one magnitude smaller than that of the incineration processes, thereby greatly extending the life of existing landfill sites. In regions without landfill sites, the direct melting process allows the volume reduction and recycling of MSW without constructing new, large-scale landfills.

2.2 Outline of coke-bed direct melting process[4]

Fig. 2 schematically illustrates the reactions taking place in the coke-bed direct melting furnace. The melting furnace is a packed bed (shaft furnace) and is divided into the top preheating and drying zone (gas temperature of 200 to 300°C), middle thermal decomposition zone (gas temperature of 300 to 1,000°C), and bottom combustion and melting zone (gas temperature of 1,500°C or more). MSW is charged together with limestone and coke from the top of the furnace, and its moisture is evaporated in the preheating and drying zone. The dried MSW descends into the thermal decomposition zone where it is thermally decomposed

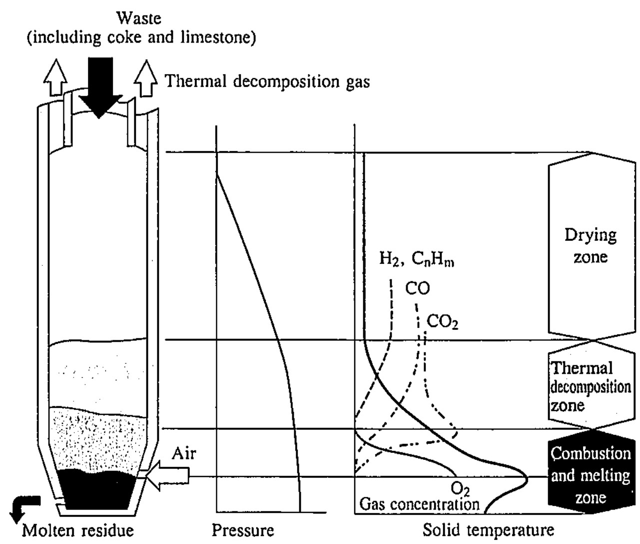
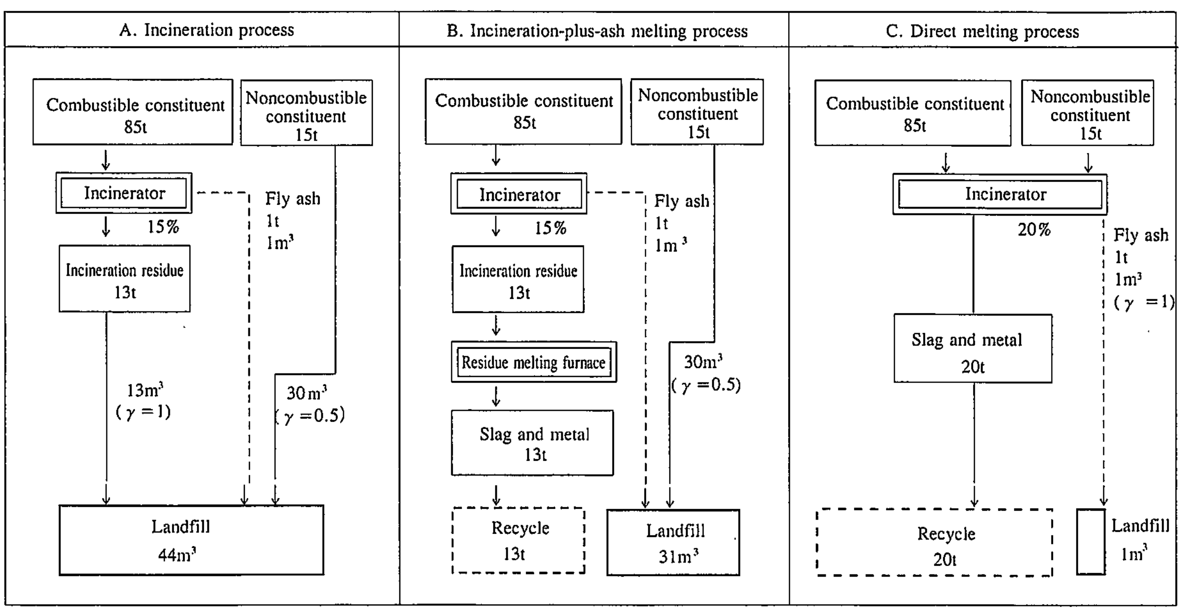


Fig. 2 Schematic illustration of reactions in melting furnace



Note: Amount of fly ash is estimated at 1% of waste volume handled, and γ is density.

Fig. 1 Final disposal volume comparison of MSW disposal processes into combustible gas and particles. The combustible particles are burned in the combustion zone. The high-temperature combustible particle combustion residue (ash) drops together with the coke into the melting zone. Air supply holes, called tuyeres, are provided in the bottom of the furnace. Oxygen-enriched air is supplied through the tuyeres to burn the coke at high temperatures and to completely melt the combustible particle combustion residue. The molten materials have the basicity (CaO/SiO_2 ratio) adjusted to a proper level by the limestone and exit the tap hole while maintaining appropriate fluidity.

2.3 Features of coke-bed direct melting furnace

The coke-bed direct melting furnace has the following features.

(1)Minimization of final disposal volume

Since MSW is melted at high temperatures in the coke bed, the resultant molten materials (slag and metal) are stable and uniform in properties, highly valuable for reuse as a variety of materials, and minimize the final disposal volume.

(2)Simple equipment configuration and high equipment reliability

The combustible and noncombustible constituents can be processed together without any special preparation, such as shredding, sorting, and drying, except for oversize bulky waste that must be shredded. The necessary equipment is thus simple in configuration and highly reliable.

(3)Effective utilization of energy

The energy generated by the melting of the MSW can be recovered as electricity and heat.

3. Research on Improvement of Direct Melting Process with Demonstration Furnace

3.1 Goal of improved process

R&D work was initiated on an improved direct melting process for sharply reducing auxiliary feed materials consumption.

3.2 Basic configuration of improved process

As shown in **Fig. 3**, the amounts of heat required in the preheating and drying, thermal decomposition, and melting steps of the direct melting furnace are supplied by MSW (strictly speaking, combustible particles) and coke combustion. If a greater amount of MSW is burned in the furnace, the amount of heat to be supplied by coke combustion can be reduced. Lowering coke consumption can cut the level of oxygen-enriched air supplied for coke combustion and the amount of oxygen produced by a pressure swing adsorption (PSA) oxygen generator for air enrichment. The improved direct melting furnace process was thus designed to lower coke and PSA oxygen consumption by boosting MSW combustion. The following two equipment modifications were planned to accomplish the above-mentioned process improvements.

(1)Air supply tuyeres for MSW combustion were installed above the conventional oxygen-enriched air supply tuyeres.

(2)The inside profile of the furnace was optimized to promote MSW combustion.

3.3 Basic policy for improved furnace demonstration test

The validity of the improved process was already verified by research with the small 10-t/d pilot furnace. The small pilot furnace was operated on 9 to 17 t/d of MSW. As a result, compared with the conventional process the improved process was found to be capable of reducing the consumption of coke and PSA oxygen by 57% and 38%, respectively[2]. To incorporate these improvements in the commercial process, a decision was made to conduct demonstration testing of a commercial-sized plant. The size of the demonstration plant was set at 50 t/d by considering the capacity of a commercial melting furnace under planning (see **Fig. 4**). The scale-up factor from the small pilot furnace was 3 to 5. If the performance of the improved process was verified by the demonstration test, the commercial plant will be capable of being designed with a maximum capacity of 400 t/d at a similar scaleup factor ((50-80 t/d) × (3-5) = 150-400 t/d).

The Kamaishi City government in Iwate Prefecture permitted Nippon Steel to use one of two MSW direct melting furnace lines (completed in 1979) at its incineration plant for the demonstration test. The equipment necessary for the improvement research was brought into the incineration plant and assembled to build the demonstration plant.

3.4 Demonstration plant

3.4.1 Demonstration plant

The equipment flow of the demonstration plant is shown in

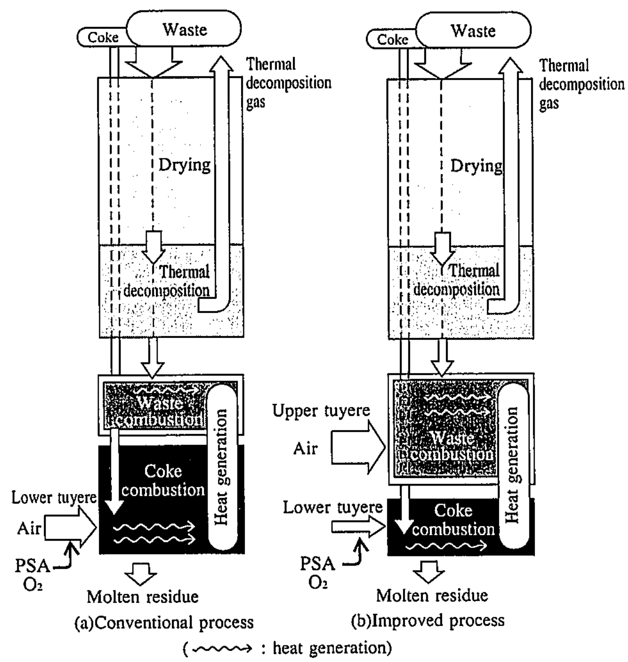


Fig. 3 Improved melting furnace process

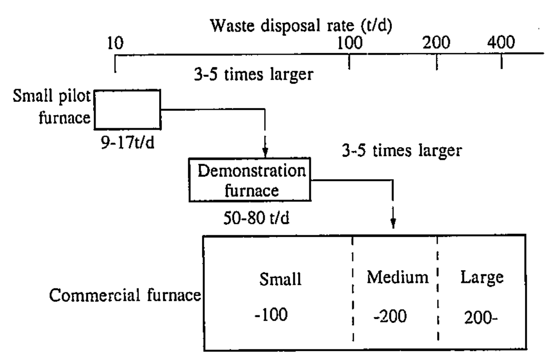


Fig. 4 Demonstration and commercial furnaces

Fig. 5. The general view of the incineration plant is shown in **Photo 1**, the general view of the melting furnace is presented in **Photo 2**, and the main specifications of the melting furnace are given in **Table 1**.

The incineration plant in Kamaishi City has two MSW direct melting furnaces with a nominal capacity of 50 t/d each. It mainly consists of: waste receiving and feeding equipment; auxiliary material feeding equipment; two lines of melting furnace equipment; two lines of combustion equipment; two lines of combustion gas cooling equipment; water supply and returning equipment; waste heat utilizing equipment; two lines of ventilation equipment; two lines of molten residue disposal equipment; ash disposal equipment; utility equipment; and electrical equipment and instrumentation. Of the two 50-t/d melting furnaces, one is normally operated in view of MSW generation balance. Prior to the demonstration test, one melting furnace and some items of associated equipment were replaced by those of improved design.

The melting furnace was lined with a high-alumina monolithic refractory, and the air supply tuyeres were water cooled. As shown in **Fig. 5**, MSW and shredded oversize bulky waste are dumped into the pit, weighed by the crane, and fed by the waste feeding equipment into the furnace. The required amounts of coke and limestone are simultaneously fed into the furnace. The waste feeding equipment is built with double gas seal valve construction and designed to completely isolate the furnace atmosphere from outside air. The waste is charged into the melting furnace when the signal from the burden level meter installed in the furnace indicates that the burden level has dropped to the specified level. The molten materials are discharged through the tap hole in the bottom of the furnace and rapidly cooled in the water granulation tank into granules. The granules are separated by the magnetic separator into slag and metal and sold. The thermal decomposition gas is discharged from the top of the furnace and completely burned by the combustion chamber burners. The combustion waste gas heat is recovered by the hot-water generator, cooled by the gas cooler, dedusted by the electrostatic precipitator, and released from the stack through the induced-draft fan. The dust collection ash is rendered nonpolluting by adding a reagent. A forced-draft fan is used to blow air into the furnace. The improved design has tuyeres installed in two rows. Air enriched with PSA oxygen is supplied through the upper row of tuyeres, and air alone is supplied through the lower row of tuyeres.

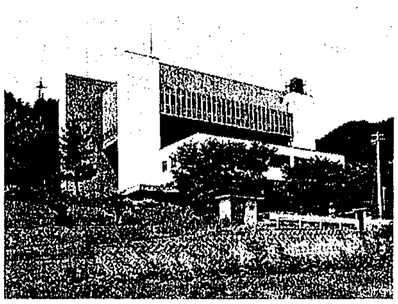


Photo 1 General view of incineration plant in Kamaishi City, Iwate Prefecture

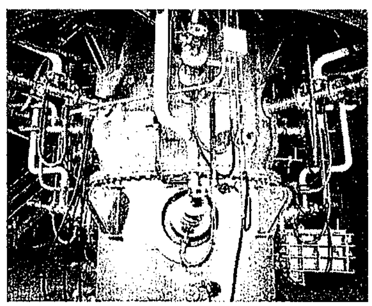


Photo 2 General view of improved melting furnace

Table 1 Main specifications of demonstration plant

Item		Specification
Oversize bulky waste shredder		Horizontal rotary typ (30 t/5 h)×1 unit
Waste pit		1,000 m³
Waste crane		1.5 m³ (grab)×2 units
Nominal capacity of melting furnace		50 t/d×2 units
Tuyere	Lower	Oxygen-enriched air at room temperature
	Upper	Air at room temperature
Combustion chamber		Three-stage air supply type
Hot-water generator		Jacket type (heating and hot-water supply)
Gas cooler		Water spray type
Dust collector		Electrostatic precipitator
Residue magnetic separator		Wet magnetic separator
Equipment for rendering ash harmless		Chemical-type nonpollating method

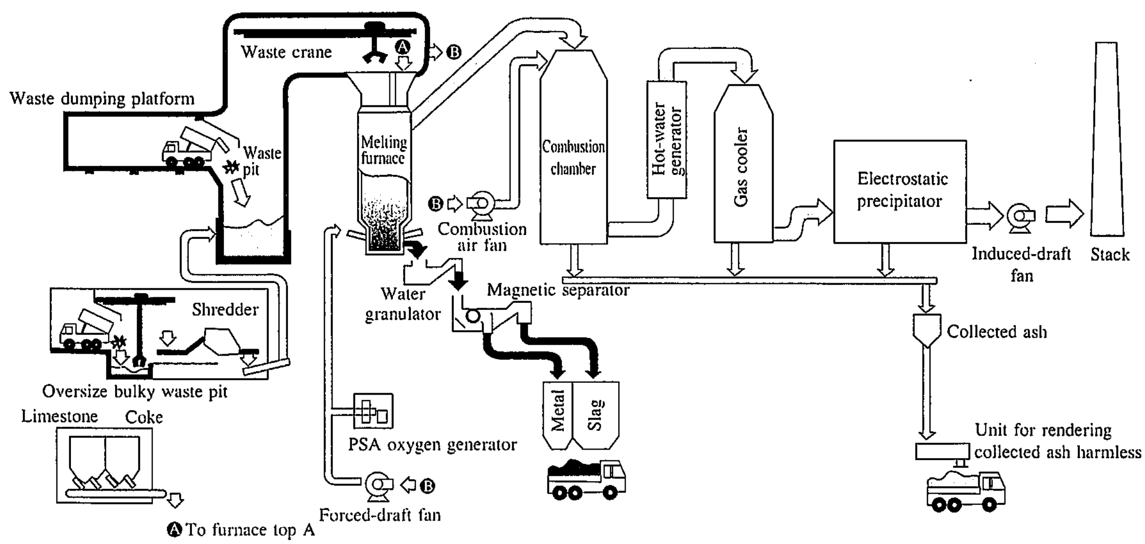


Fig. 5 Flow sheet of demonstration plant

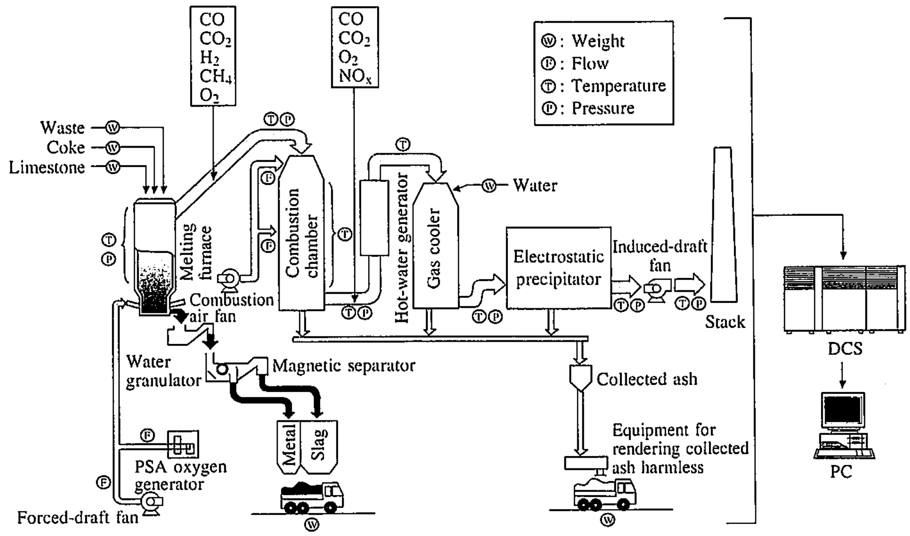


Fig. 6 Instrumentation system of demonstration plant

Balanced draft control is effected to keep the top pressure of the furnace at ±0 Pa.

3.4.2 Instrumentation system

Fig. 6 shows the instrumentation system of the demonstration plant. The waste, coke and limestone feed rates and the molten residue generation rate are all measured and recorded. The pressure and temperature in the melting furnace and combustion chamber and the flow rate of air supplied to the melting furnace and combustion chamber are all continuously recorded. The composition (CO, CO_2, O_2, CH_4, H_2) of thermal decomposition gas leaving the top of the furnace and the composition (CO_2, O_2, CO, NO_x) of the waste gas leaving the combustion chamber are also continuously measured. These data are introduced into the distributed control computer (DCS), transmitted to data logging and analyzing computers, and used for the real-time analysis of material balance, among other things.

3.5 Test methods

The transportation and installation of demonstration plant equipment were completed by March 1995, and the operation of the demonstration plant commenced in April 1995. Since the incineration plant is the only one of its kind in Kamaishi City, all waste (including combustible, noncombustible, and oversize bulky waste) generated in the city was handled in the improved melting furnace. Kamaishi City has the following MSW disposal policies:

(1)Recyclable waste is sorted at source as much as possible then collected,

(2)Non-recyclable waste (combustible and noncombustible constituents collected together) and oversize bulky waste are all transported to the incineration plant and are burned in the melting furnace. The residue from the melting furnace is separated into slag and metal and used in various applications.

3.6 Test results

3.6.1 Compositions of test waste and auxiliary feed materials

The analysis results of the waste and auxiliary feed materials used in the demonstration test are given in **Tables** 2 to 4.

3.6.2 Melting furnace mass balance calculation model

To quantify the increase in the amount of heat generated by the combustion of waste in the melting furnace, the behavior of carbon that governs the generation of heat in the melting furnace,

Table 2 Analysis results of waste (collected in Kamaishi City)*1

Composition by type (%-dry)	
Paper and rags	31.6
Vinyl, rubber, etc.	17.3
Wood, bamboo, rice straw, etc.	8.6
Vegetables and foodstuffs	18.0
Noncombustibles	19.6
Others	4.8

Analysis item		
Three components	Moisture	40.6
	Ash	18.5
	Combustible	41.0
	(%-wet)	
Ultimate analysis	Carbon	19.4
	Hydrogen	2.9
	Oxygen	17.7
	Nitrogen	0.5
	Combustible sulfur	0.07
	Volatile chlorine	0.17
	(%-wet)	
Heating value	Higher heating value of combustible waste (kcal/k-dry)	4,331
	Higher heating value of wet waste (kcal/k-wet)	2,028
	Lower heating value of wet waste (kcal/k-wet)	1,629
	Calculated heating value*2 (kcal/m³)	1,621
Apparent specific gravity (kg/m³)		342

*1 Average values of six analyses made from April to November, 1995

*2 Steuer equation

Common
dry : Dry basis
wet : Wet basis

Table 3 Coke analyses

Total moisture (%AR)		2.7
Proximate analysis	Moisture	0.2
	Ash	7.5
	Volatile matter	1.2
	Fixed carbon	91.1
	(%-dry)	
Ultimate analysis	Ash	7.5
	Carbon	90.1
	Hydrogen	0.5
	Oxygen	0
	Nitrogen	1.2
	Combustible sulfur	0.5
	(%-dry)	

Table 4 Limestone analyses

Total moisture		2.0
Composition	Ignition loss	41.8
	CaO	53.7
	Others	4.5
	(%-wet)	

AR: As-received basis
dry: Dry basis

more specifically, how the supplied carbon is consumed in what reaction form, was analyzed. The analysis was performed by using the mass balance model shown in **Fig.** 7.

3.6.3 Carbon consumption forms

Fig. 8 shows the forms in which carbon is consumed in the melting furnace. The vertical axis indicates values relative to the total carbon content of 100. The total amount of carbon supplied to the melting furnace consists of carbon from coke and carbon from the waste. The carbon supplied by the waste is subdivided into a first fraction contributing to the combustion reaction (waste combustion in **Fig.** 8), a second fraction contributing to the thermal decomposition reaction (thermal decomposition in **Fig.** 8), and a third fraction contributing to the solution loss reaction (SL reaction in **Fig.** 8). The proportions of these three fractions were estimated by the model shown in **Fig.** 7. Compared with the conventional process in the small pilot furnace stage the improved process has a greater waste combustion fraction and a smaller coke combustion fraction without appreciable changes in the waste gasification and other fractions. These results mean that the original goal of the improved process was accomplished.

The effect of the improved process in reducing the consumption of auxiliary feed materials in the commercial melting furnace is shown in **Fig.** 9. To exclude the effect of difference in waste quality between the improved and conventional processes, the coke feed rate (kg/h) and the PSA oxygen feed rate (Nm³/h) per unit amount of carbon (kg/h) supplied from the wastes are plotted along the vertical axis against 100 for the conventional process. The improved process recorded coke and PSA oxygen consumption rates 51% and 43% of those for the conventional process.

3.6.4 Properties of melting residue

The general views and compositions of the melting residue are shown in **Photo** 3 and **Fig.** 10, respectively. The slag is gray

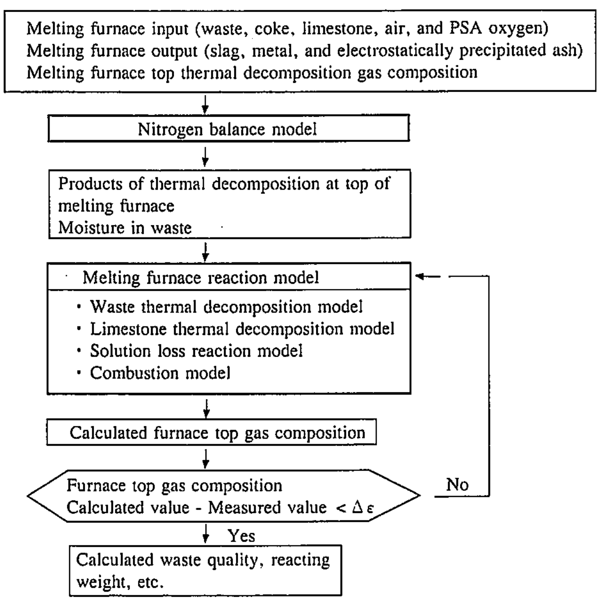


Fig. 7 Model for calculating mass balance in melting furnace

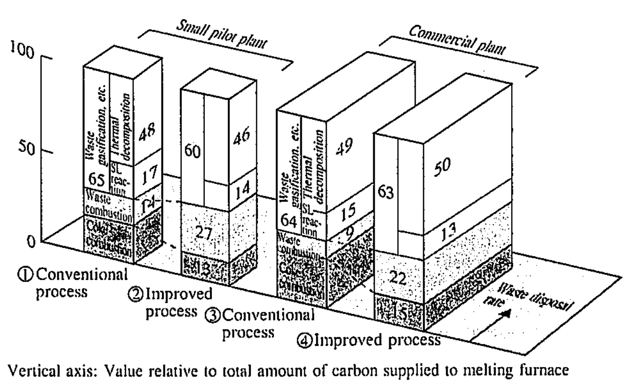


Fig. 8 Forms of carbon consumption in melting furnace

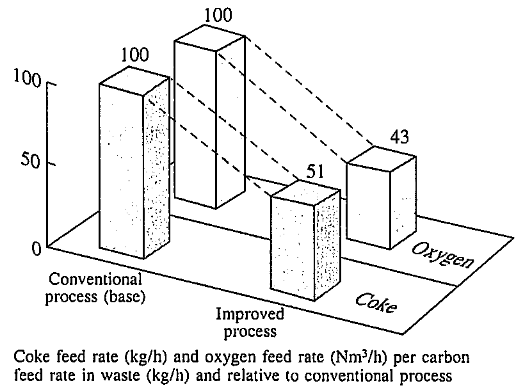


Fig. 9 Effect of improved melting furnace in reducing consumption of auxiliary feed materials

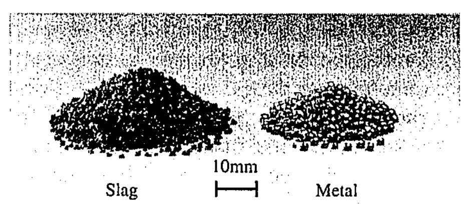


Photo 3 General view of melting residue

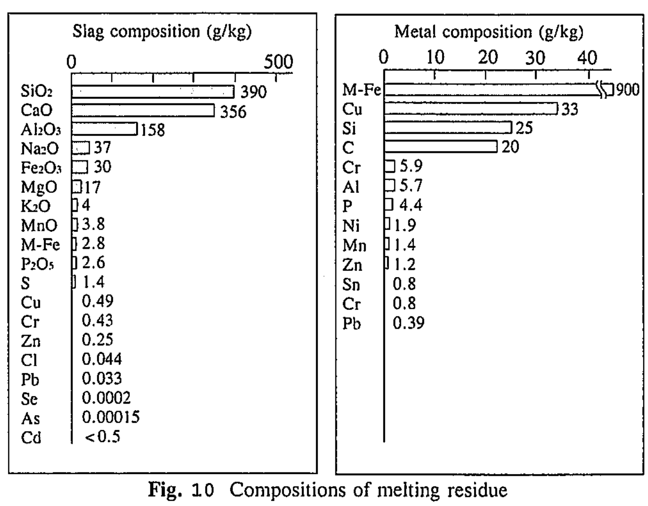


Fig. 10 Compositions of melting residue

Table 5 Slag elution test results (mg/L)

	Test result	Soil standard
As	<0.005	<0.01
Cd	<0.001	<0.01
Cr^{6+}	<0.05	<0.05
T-Hg	<0.0005	<0.0005
Pb	<0.01	<0.01
Se	<0.01	<0.01

with homogeneous glassy particles, and is mainly composed of SiO_2, CaO and Al_2O_3. The metallic iron content is less than 0.3%, attesting to the efficient removal of iron by the magnetic separator. The slag elution test results are presented in **Table 5**. These met the soil environmental standards specified in Notification No. 25 of the Environment Agency of Japan.

The metal contains homogeneous particles with metallic luster and is composed of more than 90% metallic iron.

3.6.5 Utilization of melting residue

(1)Slag

Taking advantage of its low impurity content and good homogeneity the slag is sold ex the incineration plant as a substitute for natural sand. It is used as fine aggregate for asphalt paving mixtures in private construction projects.

(2)Metal

Capitalizing on its high metallic iron content and good homogeneity, the metal is sold ex the incineration plant as material for construction machinery counterweights.

4. Study of Slag Utilization Technology

4.1 Outline

The slag produced in the melting furnace is already used in private applications as noted above. The slag was tested for its basic properties to expand its reuse as a fine aggregate for asphalt paving mixtures for public roads.

4.2 Basic property test results

4.2.1 Aggregate test results

The aggregate test results of the slag are shown in **Table 6**.

(1)Particle size distribution

The April 1995 test data of **Table 6** are the average values and standard deviation of three samples taken on different days. The particle size variability (standard deviation σ) among the three samples was small, and the particle size was even. The low content of 75 μm and finer dust fractions indicates that the slag is a clean material.

Table 6 Slag aggregate test results

Item \ Sample		Samples taken in April 1995: Average	Samples taken in April 1995: Deviation σ	Sample tested in May 1994	Reference target value
Moisture content (%)		4.6	0.4	—	—
Particle size	9.5mm	100.0		100.0	100
	4.75mm	99.7		99.8	90-100
	2.36mm	94.2	0.8	94.9	80-100
	1.18mm	56.7	2.8	57.4	—
Particle size distribution by weight (%)	600μm	19.8	2.7	22.1	25-65
	300μm	6.8	0.6	5.7	10-35
	150μm	2.6	0.2	2.0	2-10
	75μm	1.2	0.1	0.8	0-5
Specific gravity	Apparent	2.798	0.020	2.807	—
	Saturated surface-dry	2.770	0.028	0.761	
	Bulk	2.754	0.034	2.735	
Water absorption (%)		0.57	0.21	0.94	—
Unit weight (t/m^3)	Standard	1.488	0.033	1.491	—
	Light-duty	1.321	0.028	1.378	—

About 75% of the particle size distribution is concentrated in the particle size range of 600 μm to 2.36 mm, and the fraction passing through 600 μm is insufficient compared with the reference target value. It is desirable that the slag should be used together with fine sand.

(2)Specific gravity, water absorption, and unit weight

The test results show no particular problems with these properties.

(3)Summary

The slag from the melting furnace is considered to meet the quality standards required of asphalt concrete aggregate when used singly or in combination with natural fine aggregate. (It is suited for use in combination with natural fine aggregate and is free from dirt, sludge, organic matter and other harmful substances.)

4.2.2 Asphalt paving mixture test results

An asphalt paving mixture in which the slag from the melting furnace was substituted for 10% of natural sand was tested in comparison with an asphalt paving mixture in which only natural sand was used.

(1)Both mixtures fell within the design particle size range.

(2)Both mixtures met the standard Marshall properties (density, stability, flow value, air void, saturation degree, and residual stability) at an optimum asphalt content.

(3)The dynamic stability of both mixtures, a flow resistance index, was close to the reference value and acceptable.

(4)The raveling wear, an index of wear resistance, of both mixtures fully met the target value of 2.0 cm^2 or less specified for surface course mixtures in snowy and cold regions.

4.2.3 Summary

The Marshall properties and durability of an asphalt paving mixture containing 10% water-granulated slag are equal to those of an asphalt paving mixture containing natural sand. This means that the water-granulated slag can be satisfactorily used as fine aggregate for asphalt paving mixtures.

4.3 Future plan

Based on the basic property test results, the water-granulated slag was paving tested in June 1995 to verify its service performance as a fine aggregate for asphalt paving mixtures. Follow-up surveys will continue to be carried out.

5. Operating Performance of Improved Melting Furnace

The waste disposal results of the improved melting furnace from April to December, 1995 are shown in **Fig. 11**. Over 205 days of operation, the improved melting furnace disposed of about 13,000 tons of oversize bulky, noncombustible and combustible waste and produced about 2,400 tons of slag and metal.

6. Delivery and Construction of Waste Direct Melting Furnaces

Table 7 lists the waste direct melting furnaces delivered and constructed by Nippon Steel.

7. Conclusions

A commercial-size melting furnace was demonstration tested with the aim of reducing the consumption of coke and PSA oxygen in coke-bed MSW direct melting furnaces.

(1)The improved melting furnace process was demonstration

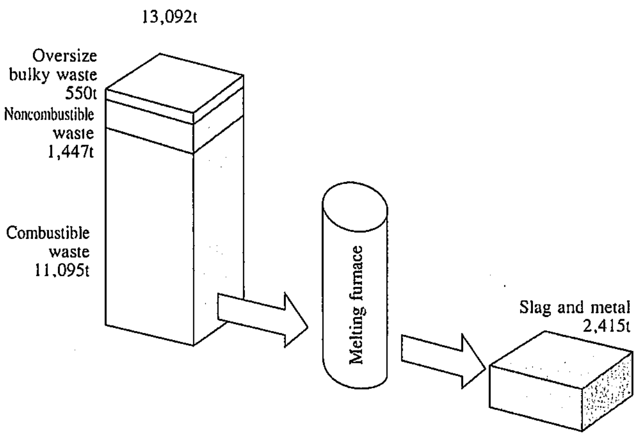


Fig. 11 Waste disposal results of improved melting furnace

Table 7 Waste direct melting furnaces delivered or constructed by Nippon Steel (as of April 1994)

Location	Kamaishi City, Iwate Prefecture	Ibaraki City, Osaka Prefecture	Ibaraki City, Osaka Prefecture
Customer	Kamaishi City government	Ibaraki City government	Ibaraki City government
Capacity	50t/d×2 furnaces	150t/d×3 furnaces	150t/d×2 furnaces
Waste	MSW (including noncombustible component)	MSW (including noncombustible component)	MSW (including noncombustible component)
Completed	August 1979	July 1980	March 1996
Waste heat utilization	Hot-water recovery	Waste heat boiler/electric power generation	Waste heat boiler/electric power generation

Location	Tatsuno City, Hyogo Prefecture	Ohkawa City, Kagawa Prefecture	Iizuka City, Fukuoka Prefecture
Customer	Tatsuno Health and Hygiene Facility Association	Kagawa Prefecture East Incineration Plant Association	Iizuka City government
Capacity	60t/d×2 furnaces	65t/d×3 furnaces	90t/d×2 furnaces
Waste	MSW (including noncombustible component)	MSW (including noncombustible component)	MSW (including noncombustible component and sludge)
Completion date	March 1997 (under construction)	March 1997 (under construction)	March 1998 (under construction)
Waste heat uses	Waste heat boiler/electric power generation	Waste heat boiler/electric power generation	Waste heat boiler/electric power generation

tested by replacing part of an existing melting furnace facility (with a nominal capacity of 50 t/d) at the incineration plant of the Kamaishi City government.

(2)The improved melting furnace was operation tested for a total of 205 days from April to December, 1995. It disposed of about 13,000 tons of MSW (including combustible, noncombustible and oversize bulky waste) and produced about 2,400 tons of slag and metal.

(3)The percentage of waste combusted in the melting furnace was increased by installing air supply tuyeres in two rows and optimizing the internal profile of the furnace.

(4)The consumption of coke and PSA oxygen as auxiliary fuels was reduced by 49% and 57%, respectively.

(5)The forms of carbon consumption in the demonstration furnace were similar to those observed in the small 10-t/d pilot furnace.

(6)The slag produced from the melting residue is similar to natural sand in both composition and elution test results and is sold ex the incineration plant for use in private construction projects.

(7)The metal produced from the melting residue is not hazardous in terms of composition and is sold ex the incineration plant as material for heavy construction machinery counterweights.

(8)To expand its scope of application for public roads, the slag was basic property tested to verify its service performance as fine aggregate for asphalt paving mixtures. It was found to be satisfactory when added at a rate of 10% to asphalt paving mixtures. It was then paving tested.

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