NIPPON STEEL TECHNICAL REPORT No. 86 JULY 2002

UDC 669 . 054 . 82 : 628 . 4

Technology of Using Molten Slag and Metal Generated from Municipal Solid Wastes

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Abstract

The melting treatment of wastes, compared with the conventional incinerating method, helps reduce the burdens on final disposal sites since wastes are made harmless, less bulky and reusable as useful resources. Of various types of melting waste, the gasifying and melting technologies are recently attracting attention. This is because, unlike incineration residue melting furnaces, the melt-solidified products are obtained without passing the state of ash, hence simplifying the equipment concerned. More than twenty years ago, Nippon Steel developed the gasifying and melting technology for a shaft furnace and has steadily refined the commercial furnace as the "direct-melting resource-recovery system." The system does not simply "treat" wastes. It positively "produces" useful resources from wastes and contributes to the promotion of a recycling-oriented society. Starting with the melting furnaces commissioned in Kamaishi City, Iwate Prefecture and in Ibaraki City, Osaka Prefecture, Nippon Steel has pursued studies on waste reutilization jointly with civil engineering and construction companies. At the currently operating facilities, nearly the entire amount of molten slag has come to be reused as aggregate in civil engineering and construction companies. This paper describes the outline of the utilization technology of molten slag.

1. Introduction

At present about 50 million tons of municipal solid wastes are generated per year, domestically. 80% of that is disposed of through incineration. It becomes necessary, however, to landfill incinerator residues and incombustibles if wastes are disposed of only by incineration, which has been the method most used to date.. This has clearly posed serious problems as seen in the pollution of the environment around landfill sites or in the necessity of securing new sites. Accordingly, much effort has been expended to develop a new waste disposal technology so that wastes can be recycled to a higher degree and the discharge of toxic substances can be controlled, including the promotion of controlling the generation of wastes.

With regard to laws relating to pollution control, the law for general measures for dioxins control and the law for the promotion of a closed loop society have been enacted as new steps toward protecting our environment and promoting recycling in the treatment of waste.

Under such circumstances, one waste disposal technology related to a method of melting wastes for treatment has attracted public at-

*1 Environment & Waterworks Solution Division tention. This method has an advantage in that it generates molten slag that can be converted to recyclable resources in place of incineration ash generated by the conventional incineration method so that the number of landfill sites can be drastically reduced.

The "direct-melting resource-recovery system" positioned as the gasification melting furnace of shaft type has been developed and put to practical use by Nippon Steel to make the most of the above advantage. This system is also excellent in combustion controllability, because it burns wastes after they have been pyrolyzed and gasified. Its other feature is that it controls toxic substances, such as dioxins, in the exhaust gases. Backed up by the operational experience extending over 20 years on the basis of long-fostered technologies in the field of iron and steel making, this system is a process in which a logistic system has been established for effective use of the melt-solidified products[1-3]. This paper introduces the quality, features, and the actual condition of the effective use of the melt-solidified products (molten slag and metal) of the direct-melting resource-recovery system.

2. Nippon Steel's melting equipment and operational condition

2.1 Outline of melting facility

The direct-melting resource-recovery system lies in directly melting municipal solid wastes, hereinafter abbreviated to waste, without an incineration process unlike the incinerator residue melting furnace in which the incineration residue discharged from the incinerator is melted. It is classified into the gasification and melting furnace of shaft type. It has four functions of drying, pyrolytic gasificaton, combustion and melting. These four functions are integrated into the shaft-type furnace as a process constituting a direct-melting system. **Fig. 1** shows the direct-melting resource-recovery system and a flowchart of treating waste.

2.2 Operational condition

Table 1 shows how this system has sufficed domestically up to the present. Since the 1st facility started operating in Kamaishi City in 1979, nine facilities have been operating satisfactorily throughout Japan. With regard to other facilities now under construction, four are expected to be started in fiscal 2001, and seven in fiscal 2002.

2.3 Resource recovery of molten slag

For effective use of melt-solidified products as a resource, it should satisfy the following conditions in terms of safety and quality:

1) Safety should be secured.
2) Slag and iron should be separated highly accurately.
3) Standards should be met according to its respective applications.

It is necessary to secure stable melt-solidified products surely to satisfy the above requirements without being influenced by the changes in the properties of wastes for melting treatment. In the direct-melting resource-recovery system, as wastes are moving downward with the rising temperatures in the melting furnace, they are heated, melted by burning coke and dripped downward through a coke bed layer with high temperature and are discharged stably as it is completely melted before it has been stored at the furnace bottom.

Several methods of evaluation can be considered relative to securing safety. It becomes necessary under the present circumstances, however, to satisfy the so-called standard of leachates of heavy metals for fear that, when molten slag was used for civil engineering and construction materials for field use, heavy metals contained in molten slag are leached and pollute neighboring land and rivers. Therefore, the former Ministry of Health and Welfare stipulated the regulatory limitation of leachate as given in **Table 2**. The regulatory limitation of leachate is given in "Concerning the promotion of enforcement of the recycling of melt-solidified products of municipal solid wastes" (The notification of the Ministry of Health and Welfare No.508, in March, 1998), and employs the soil environment standard as a criterion value by using the leachate testing method based on the public notice No.46 of the former Environment Agency.

In recent years the content of heavy metals in molten slag has become a controversial issue in consideration of the risk to the health when molten slag, effectively used, is pulverized and scattered to enter through mouth into human body.

The characteristics of molten slag are described below in terms of safety and quality in the direct-melting resource-recovery system.

2.3.1 Content of heavy metals in molten slag

Since a high-temperature reduction atmosphere is formed in the melting furnace, vaporization of low-boiling-point heavy metals is accelerated so that the transfer of the heavy metals into the slag is restricted. Accordingly, the content of those heavy metals in the slag

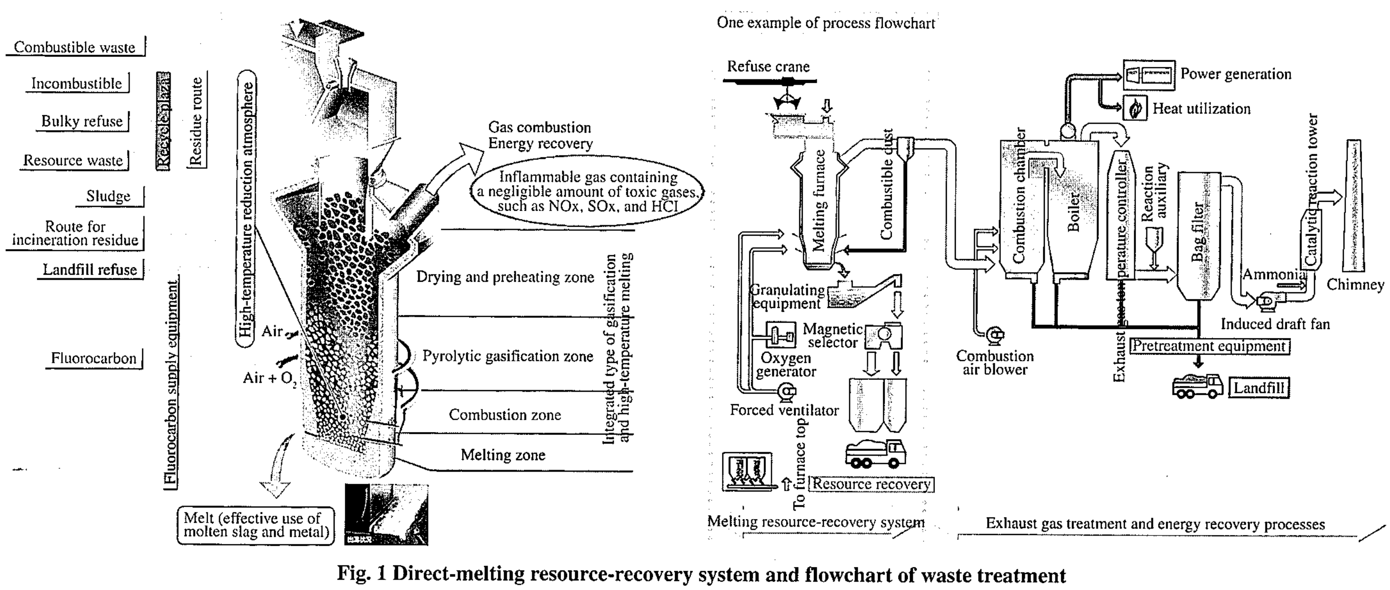

Fig. 1 Direct-melting resource-recovery system and flowchart of waste treatment

Table 1 Conditions of operation and construction of direct-melting and resource-recovery system

Facilities in operation

	Customers	Location	Facility scale/treatment capacity	Service period
(1)	Kamaishi City	Kamaishi City, Iwate Pref.	100t/day (50t/day×2 furnaces)	1979.9
(2)	Ibaraki City (1st factory)	Ibaraki City, Osaka Pref.	450t/day (150t/day×3 furnaces)	1980.8
(3)	Ibaraki City (2nd factory)	Ibaraki City, Osaka Pref.	300t/day (150t/day×2 furnaces)	1996.4
(4)	Iryuu Hygiene Organization	Tatuno City, Hyogo Pref.	120t/day (60t/day×2furnaces)	1997.4
(5)	Kagawa Prefecture Eastern Sanitation Organization	Nagao Town, Kagawa Pref.	130t/day (65t/day×2 furnaces)	1997.4
(6)	Iizuka City	Iizuka City, Hukuoka Pref.	180t/day (90t/day×2 furnaces)	1998.4
(7)	Ibaraki City (1st factory modernization)	Ibaraki City, Oosaka Pref.	150t/day (150t/day×1 furnace)	1999.4
(8)	Itojima Area Fire House Welfare Organization	Shima Town, Hukuoka Pref.	200t/day (100t/day×2 furnaces)	2000.4
(9)	Kameyama City	Kameyama City, Mie Pref	80t/day (40t/day×2 furnaces)	2000.4

Facilities under construction

	Customers	Location	Facility scale/treatment capacity	Service period
(1)	Akita City	Akita City, Akita Pref.	400t/day (200t/day×2 furnaces)	2002.4(scheduled)
(2)	Takizawa Village	Iwate Pref.	100t/day (50t/day×2 furnaces)	2002.12(scheduled)
(3)	Makimati Sotomikkamati Village Hygiene Organization	Niigata Pref.	120t/day (60t/day×2 furnaces)	2002.4(scheduled)
(4)	Kazusa Clean System Ltd.	Kisarazu City, Chiba Pref.	200t/day (100t/day×2 furnaces)	2002.4(scheduled)
(5)	Kagawa Prefecture Eastern Sanitation Organization	Nagao Town, Kagawa Pref.	65t/day (65t/day×1 furnace)	2002.4(scheduled)
(6)	Narashino City	Narashino City, Chiba Pref.	201t/day (67t/day×3 furnaces)	2003.4(scheduled)
(7)	Toyokawa Houhan Hygiene Organization	Toyokawa City, Aichi Pref.	130t/day (65t/day×2 furnaces)	2003.4(scheduled)
(8)	Kouti Eastern Environment Facilities Organization	Nakamura City, Kochi Pref.	140t/day (70t/day×2 furnaces)	2003.4(scheduled)
(9)	Tajimi City	Tajimi City, Gifu Pref.	170t/day (85t/day×2 furnaces)	2003.4(scheduled)
(10)	Ooita City	Oita City, Oita Pref.	387t/day (129t/day×3 furnaces)	2003.4(scheduled)
(11)	Koga City Sotoitiyonmati Waste Treatment Organization	Munakata City, Fukuoka Pref.	160t/day (80t/day×2 furnaces)	2003.4(scheduled)
(12)	Seinou Environment Maintenance Organization	Gifu Pref.	90t/day (90t/day×1 furnace)	2004.4(scheduled)

Table 2 Regulatory limitation of leachates of molten slag

Subject substances	Regulatory limitation of leachates
Cadmium	Below 0.01 mg/l
Lead	Below 0.01 mg/l
Hexavalent chromium	Below 0.05 mg/l
Arsenic	Below 0.01 mg/l
Total mercury	Below 0.005 mg/l
Selenium	Below 0.01 mg/l

Prepared from notification #508 of the Ministry of Health and Welfare

remains on a low level. This is very effective for preventing the leaching of heavy metals, such as lead (Pb), from the slag, thereby ensuring to render them harmless. With concentrating heavy metals into fly ash, it is also expected to make the return to metallurgical refining effective.

With Prof. Tokuda at Tohoku University and the Tokyo Metropolitan Government, joint research was conducted into clarifying the influence of an in-furnace atmosphere on the behavior of heavy metals. As a result, it was made clear that a high-temperature reduction atmosphere (under low oxygen partial pressure) lowers the distribution rate of low-boiling-point heavy metals into molten slag in the tests of treating incineration ash alone and a mixture of fly ash at the test plant with a capacity of 20 tons/day as well as in the thermodynamic analysis of the test results. **Fig. 2** shows the results of simulation using a thermodynamic reaction model by referring to the relationship between the concentration of lead (Pb) in molten slag, oxygen partial pressure, and atmospheric temperature[4,5].

The Tokyo Metropolitan Government formulated "Tokyo Metropolitan Government's guideline on the effective use of molten slag" in 2000. According to this guideline, a safety standard on generators' side was instituted as a guideline when the Tokyo Metropolitan Government uses molten slag resulting from melting treatment for civil engineering and construction materials in the future. A self-imposed control value of lead (Pb) content below 600 ppm is provided. In addition, the Soil Risk Evaluation Committee also reported that the content of lead in the soil should be below 150 ppm. All in all, it is expected that a trend will become strong toward imposing restrictions on the content of heavy metals in the molten slag in future. Since molten slag is generated by accelerated vaporization reaction at Nippon Steel, the content of lead (Pb) is almost equal to that of natural sand in a range between several to 30 ppm. This may mean that the molten slag thus generated is safe with the harmful element minimized in content.

2.3.2 Influence of metal iron in molten slag

The presence of metal iron in molten slag is harmful because it rusts due to oxidation and expands in volume. This makes it neces-

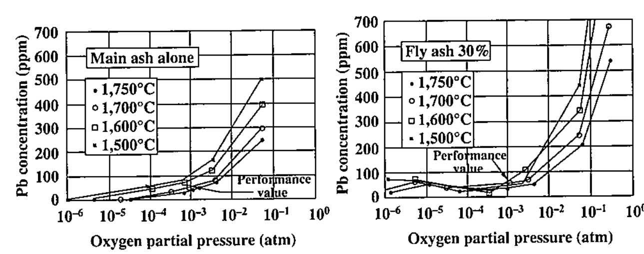

Fig. 2 Relationship between concentration of lead (Pb) in slag and oxygen partial pressure and atmospheric temperature

sary to separate metal iron from molten slag highly precisely. The magnetic selector developed independently enables to control the content of metal iron in molten slag to below 0.5%. However, it is necessary to separate and solidify slag and metal as independent granules respectively for achieving a high magnetic selection effect when the melt-solidified products were granulated by water-cooling. It is considered that high temperature induced by burning coke and adjustment of basicity with limestone to enhance the fluidity of slag is highly effective for achieving the objective.

The fine-quality slag thus produced can be used effectively for civil engineering and construction materials as substitutes for natural sand. It is already enjoying high reputation in the distribution market as the surface-layer concrete aggregate of an interlocking block. It was also put to practical use in its early stages for the public road as the aggregate of asphalt. The follow-up extending over 5 years has proven that it can safely be used effectively.

As for the metal iron as well, it is marketed as a counterweight for heavy construction machinery, because it is granulated and can be handled easily.

For keeping economically stable transactions after securing users of molten slag and metal it is indispensable to search and maintain a logistic channel. The company's expertise fostered in distributing slag of steel making is contributing much to this business.

3. Amounts and qualities of molten slag and metal

Beginning with two Nippon Steel's melting facilities that started running in Kamaishi City, Iwate Prefecture in 1979 and in Ibaraki City, Osaka Prefecture in 1980 respectively, developing investigative studies of the effective utilization of molten slag, which is discharged from the facilities delivered by Nippon Steel. Civil engineering and construction materials were pursued between Nippon Steel and the aggregate suppliers. This has resulted in the effective utilization of almost all the molten slag generated at the melting facilities.

3.1 Amount of molten slag generated at delivery facilities

The amount of molten slag generated at Nippon Steel's delivery facilities was a little over 10 thousand tons in 1995, increasing to a threefold amount or over 30 thousand tons in 1998, and further to a little less than 40 thousand tons in fiscal 2000. It is expected to increase to 110 thousand tons in fiscal 2003. On the other hand, there were only two melting facilities running where molten slag was generated in fiscal 1995, and now nine facilities are running in fiscal 2000. Furthermore, melting facilities are expected to increase to 20 in fiscal 2003, and molten slag will come to be generated all over Japan (See **Fig. 3**).

3.2 Examples of effective utilization of molten slag

As described above, the molten slag generated at the melting facilities now running is almost totally utilized. Some of them are effectively used for fine aggregate as the secondary product of concrete in Ibaraki and Iizuka cities and the others are used as fine aggregate of asphalt for the public road in Kamaishi city.

Those examples are described below:

3.2.1 Example of effective utilization in Ibaraki City, Osaka Prefecture

Table 3 shows the amount of molten slag generated at Ibaraki Municipal Public Health Center in fiscal 2000. About 15,000 tons of molten slag and about 7,000 tons of metal were generated in fiscal 2000, amounting to a total of a little over 20,000 tons. They are effectively utilized almost totally.

Molten slag, when granulated by water-cooling, is formed into gray sand, less than 4 mm in maximum particle diameter. As its fineness modulus is around 3.0, it can be regarded as coarse sand.

Table 4 shows the chemical components constituting molten slag and metal. About 37% is SiO_2 caming from ash content of waste, about 17%, Al_2O_3, and about 37% is CaO almost originated from limestone is mainly added for improving the fluidity of slag, with the three components accounting for about 90% of the total. As above-described, heavy metals, such as lead, included in waste are vaporized in the melting furnace, remaining by as little as 10 ppm in the slag. This also satisfies the limitation of leachates of heavy metals related to the soil. σ indicates the annual change in chemical components of molten slag and metal, and the ranges of fluctuation are stably small.

On the other hand, the metal looks like a globule with an average diameter of about 5 mm, and its bulk density is about 3.0. It is composed mainly of iron contained in waste, accounting for about 86% of the total. Other components, such as carbon, silica, and copper are contained by some % respectively.

The molten slag and the metal, generated at Ibaraki Municipal Public Health Center, are primarily stored in separate hoppers in the Center, and sold by bulk to private logistic companies, which in turn transport them to respective aggregate suppliers for sale. The molten slag that Ibaraki City sells is mainly used for the aggregate of a secondary concrete product, which is sold mainly to the manufacturers of interlocking blocks and cavity blocks for construction use.

There are two points to which attention should be paid in terms of quality for use as fine aggregate for concrete as follows:

1) Any concrete in which aggregate low in density and high in water

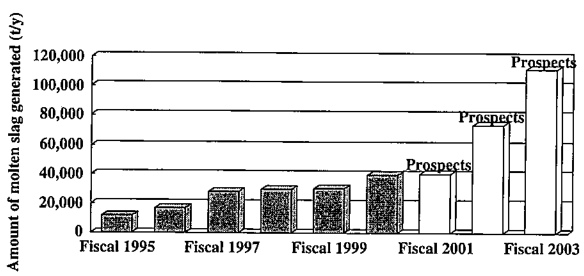

Fig. 3 Transition of amounts of molten slag generated from facilities delivered by Nippon Steel

Table 3 Amount generated of molten slag and metal in Ibaraki City

Fiscal year when molten slag and metal were effectively used	Molten slag	Metal
2000	14,800t	6,120t

Table 4 Values of chemical components of molten slag and metal (Example of molten slag and metal in Ibaraki City)

Chemical composition of slag (%)			Chemical composition of metal(%)		
	Average	σ		Average	σ
SiO_2	37.44	3.17	Fe	86.49	3.15
CaO	36.81	2.94	C	2.84	0.33
Al_2O_3	17.07	1.59	Si	5.52	1.18
MgO	1.73	0.18	Mn	0.40	0.08
Na_2O	3.49	0.81	P	1.20	0.44
K_2O	0.47	0.29	S	0.04	0.13
S	0.28	0.04	Cu	2.79	0.55
FeO	0.53	0.29	Ni	0.20	0.05
M-Fe	0.36	0.11	Cr	0.43	0.08

absorption generally induces decreases in strength and elastic modulus. This makes it inevitable to control the density and water absorption of the aggregate. It therefore becomes necessary to confirm concrete strength beforehand by the compression test.

2) A certain kind of mineral reacts with alkali in concrete to form a silicate that swells, as it is called the alkali-silica reaction. This makes it necessary to carry out an alkali-silica reaction test before using.

As molten slag is similar in property to natural aggregate, it can be used as substitutes for natural sand, crushed sand, and fine aggregate. **Table 5** shows the standard of quality of interlocking blocks (Summary of pavement design and construction work by the Interlocking Block Association), which stipulates to satisfy bending strength. **Table 6** gives the bending strengths of interlocking blocks in which molten slag, generated by water-cooling in Ibaraki Public Health Center, is mixed by 20% and 30% of the total aggregates respectively. As this Table shows, their bending strengths are superior to that of the standard given in Table 4 and it is confirmed that they can be safely used. The alkali-silica reaction was not observed in molten slag as in blast furnace slag, either.

Recently, every factory is doing its best to improve its production technology, thus enabling to substitute molten slag for about 30% of the aggregate. **Fig. 4** shows the examples of interlocking blocks in which molten slag are used as aggregate.

On the other hand, metal is used as a weight aggregate to be poured together with cement mortar into the inside of a steel counterweight to be mounted on the rear of a construction machine. The metal sold in Ibaraki City unexceptionally used as a weight aggregate by counterweight manufacturers.

Table 5 Standard of interlocking blocks

Kind	Bending strength	Remarks
Ordinary interlocking block	50kgf/cm²	Aggregate shall be clean, strong, and durable, and have a proper particle size. In addition, it should not contain harmful substances, such as refuse, mud, organic matter, and thin and slender stone pieces.
Permeable interlocking block	30kgf/cm²	
Interlocking block for vegetation	40kgf/cm²	

Table 6 Strength of interlocking blocks when molten-slag aggregate is used

Blending	Bending strength (kgf/cm²)
Molten slag mixing ratio of 20%	68.5 (67.8-69.4 N=3)
	59.7 (54.7-66.2 N=3)
Molten slag mixing ratio of 30%	82.1 (70.4-90.7 N=9)

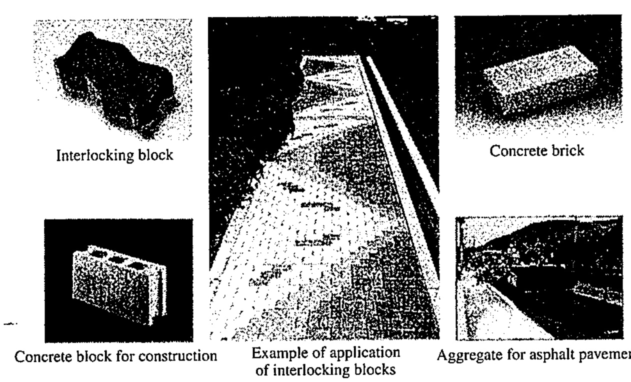

Fig. 4 Interlocking blocks and examples of application of interlocking blocks and hollow blocks for construction

3.2.2 Example of effective use by Iizuka City, Fukuoka Prefecture

The Iizuka Municipal Clean Center, which started running after 1998, is selling total molten slag generated there after the same year to neighboring interlocking block manufacturers via private logistic companies. **Table 7** shows the amounts of molten slag and metal generated in fiscal 2000. With the technology accumulated of effective use of molten slag preceded by Ibaraki City, molten slag has come to be effectively used immediately after the start of operation of the melting facility. Molten slag is substituted for not more than 30% of the total aggregates for interlocking blocks.

3.2.3 Example of effective use by Kamaishi City

Kamaishi City, Iwate Prefecture, started studying the effective use of molten slag for asphalt aggregate after 1995. Since fiscal 1997 almost all the molten slag generated by the melting facility has been effectively used up to the present for asphalt aggregate. **Table 8** shows the total amounts of molten slag and metal generated in Kamaishi City.

The example of road construction in Kamaishi City is introduced in this paper relative to the procedure of using molten slag for the surface and basic layers of the asphalted road[6-8].

When molten slag is used as a substitute for asphalt aggregate sand, it should undergo several steps of testing its physical properties and safety before it is actually used for asphalt pavement. **Fig. 5** shows one example of the procedure of a long-term follow-up before the actual application to pavement. In step (1) molten slag was subjected to the aptitude test relative to its independent particle distribution and leaching, and confirmed usable. In step (2) the molten slag judged usable was blended for use as an aggregate for an asphalt mixture, and the resulting mixture was subjected to an indoor aggregate mixture test.

In this step a leaching test was also carried out as an asphalt mixture, and the mixture was confirmed to meet the soil environment standard value. Molten slag, when mixed to the extent of 10%, was

Table 7 Amount generated of molten slag and metal in Iizuka City

Fiscal year when molten slag and metal were effectively used	Molten slag	Metal
2000	2,599t	479t

Table 8 Amount generated of molten slag and metal in Kamaishi City

Fiscal year when molten slag and metal were effectively used	Molten slag	Metal
2000	5,214t	1,537t

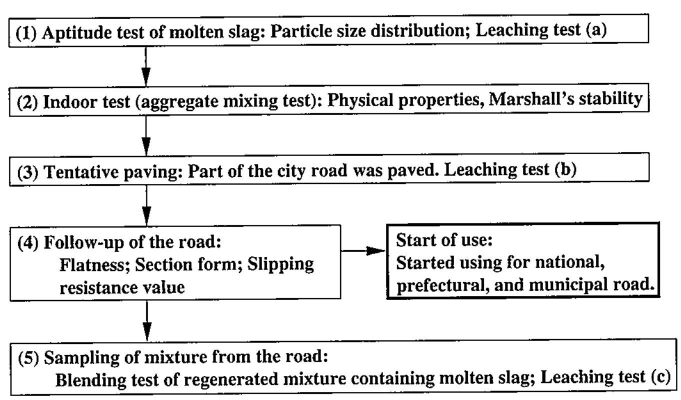

Fig. 5 Steps of research into effective use of aggregate for asphalt

found to stand comparison with a natural sand blending in Marshall's stability.

In step (3) an asphalt mixture, in which molten slag is used, was applied tentatively to the public roadwork. A generally used asphalt mixture, in which natural sand is used, was also applied to the work in the neighboring work area for comparison. In addition, as the subject area for the pavement test, we selected two areas where traffic is heavy and light, and measured road flatness, rutted amounts, and slipping resistance values. A long-term follow-up of the road was carried out ((4) Follow-up of the road).

Table 9 shows the findings of the long-term follow-up of the road. Two work areas were selected: one is with heavy traffic (Area A), and the other, with light traffic (Area B). The follow-up of the road was carried out six times in five years. No difference was observed between the molten-slag mixture and the ordinary one after five years. The molten slag mixture also satisfied the soil environment standard value in the leaching test, and was judged equal, when used as an aggregate for an asphalt mixture, to natural aggregate in property. Thus, the use of molten slag started. Molten slag is now used even for the prefectural and national roads as an aggregate for road construction.

Furthermore, in compliance with the request for the recycling of asphalt pavement, it was evaluated whether the molten-slag mixture, which had served for three years, can be recycled, and confirmed it recyclable. **Fig. 6** shows an example of road construction using molten slag as an aggregate for asphalt pavement.

4. Conclusion

If the melt resulting from melting wastes can be stably converted to resources, this waste melting treatment can be one of the most powerful methods for the realization of a closed loop society. This requires a great change in our concept from the conventional "treatment" to "production." Melting treatment should aim not only at melting only, but also at generating fine-quality slag suitable for respective applications. It therefore becomes necessary to pay attention to quality control correspondingly. It is Nippon Steel's technology of "direct-melting resource-recovery system" that has truly preceded a trend involving waste treatment. Nine melting facilities have been in operation throughout the country since the first facility started operation in Kamaishi City in 1979. And twelve facilities are now under construction. We have promoted ever since the effective use of the melt-solidified products in joint cooperation with civil engineering and construction companies and road construction companies by trying to secure stably the quality of it and establish logistic routes. This has resulted in the effective use of almost all the molten slag, which is generated in melting facilities.

Today, the promotion of the effective use of molten slag is being considered by trying to improve its quality and to expand its applications in the future as well. In that way, better contributions to the formation of a closed loop society by utilizing the limited resources to the utmost will be possible.

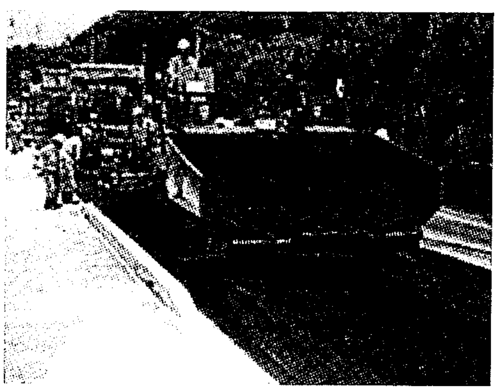

Fig. 6 Example of using for road construction aggregate

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Table 9 Results of follow-up of slag for asphalt pavement

			July, 1995	November, 1995	April, 1996	September, 1996	July, 1998	July, 2000	Remarks
			-	4 months after	9 months	1 year&2 months	3 years after	5 years after	
Flatness	Area A	General	1.268	1.483	1.208	1.225	1.270	1.530	Target σ = below 2.4
		Slag used	1.499	1.598	1.210	1.115	1.240	1.340	
	Area B	General	1.896	2.068	1.867	2.060	1.730	1.460	
		Slag used	1.078	1.248	0.915	1.249	1.110	1.56	
Rutted amount	Area A	General	12.3	13.0	12.7	11.3	12.0	10.7	
		Slag used	13.3	12.7	12.7	12.0	12.0	11.7	
	Area B	General	10.0	10.0	10.3	9.7	10.7	16.0	
		Slag used	13.7	14.0	13.7	13.7	13.3	14.0	
Slipping resistance value: BNP value	Area A	General	60	66	62	60	65	65	Target BNP value = above 50
		Slag used	59	63	57	60	62	64	
	Area B	General	65	66	67	67	69	63	
		Slag used	67	66	67	65	68	64	