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ADVANCED SLUDGE THERMAL PROCESSES IN JAPAN

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ABSTRACT

As a result of the spread of sewerage systems, the management of growing quantities of sewage sludge is becoming an urgent need. As the method of sludge management, thermal processes have mostly been applied to the treatment and disposal of sewage sludge in Japan, because of the difficulty of finding final disposal sites. This paper describes the progress of thermal processing technologies, especially focusing on drying-incineration process systems and melting-slag recycling process systems.

KEYWORDS

Sewage sludge, drying, incineration, melting, slag

INTRODUCTION

The construction of sewerage systems has been strongly promoted by the government since the First Five-year Program for Sewerage Construction in 1963. The Seventh Five-year Program has been underway since 1991. The target of the Program is to increase the sewered populations up to 55% of the total population within the period of the program. As a result, 869 treatment facilities are in operation and the publicly sewered population ratio, that is the percentage of the population living in public sewerage service area, was estimated to be 46% on average by the end of fiscal year of 1990 as shown in Figure 1. Regarding the large cities whose populations are over one million, the publicly sewered population ratios are over 90%. In the large cities, therefore, the management of increasing sewage sludge, as shown in Figure 2, has been an urgent need.

Several countermeasures have been applied for managing the sewage sludge. The treatment for disposal, and recovery processes for sewage sludge are classified as shown in Figure 3 by the author (Hiraoka *et al.*, 1988). The sludge treatment generally consists of the mechanical processes for dewatering, thermal conversion processes and biological conversion processes. With the combination of these processes, the volume reduction, stabilization and utilization of sludge as fertilizer. The utilization of sludge as fertilizer is limited because of the toxicity of heavy metals. Because of the difficulty of finding landfill sites, the thermal process, that is, incineration and landfill of residues, has been becoming popular for reducing volume and stabilizing sewage sludge. Approximately sixty percent of dewatered sludge is incinerated in Japan at present. The multiple hearth furnace was the dominant type of sewage sludge incinerator in the early stage in which the calorific value of sludge was relatively low because calcium hydroxide and ferrous chloride were usually used for the chemical conditioning of sludge. The calorific value of sludge became higher due to the chemical conditioning of sludge. The calorific value of sludge became higher due to the increasing adoption of polymers in the chemical conditioning process. The fluidized bed furnace has become popular in terms of combustion control, instead of multiple hearth furnace, since the mid 1980s. An example of chemical and physical properties of sewage sludge is shown in Table 1. The recent proportion of furnace type is shown in Figure 4. The system of fluidized bed incineration with sludge drying and waste heat recovery is the most advanced sludge management system in Japan. The objectives of incineration process the sludge are to decrease the volume, to stabilize, and to detoxify from the view point of public health. It was clear that, when chromium compounds are contained in sludge, because trivalent chromium compounds convert to hexavalent chromium compounds which are one of the toxic substances in the incineration process based on our researches (Hiraoka *et al.*, 1977). Melting processes have been developed for stabilizing the heavy metals such as chromium compounds, and the melted slag can be utilized as construction materials. Melting processes are developing as an effective measure of sludge management. The author has been deeply involved in developing the thermal processes, especially the drying incineration process systems and melting-slag utilizing processes systems. Several examples designed by the author's group will be introduced.

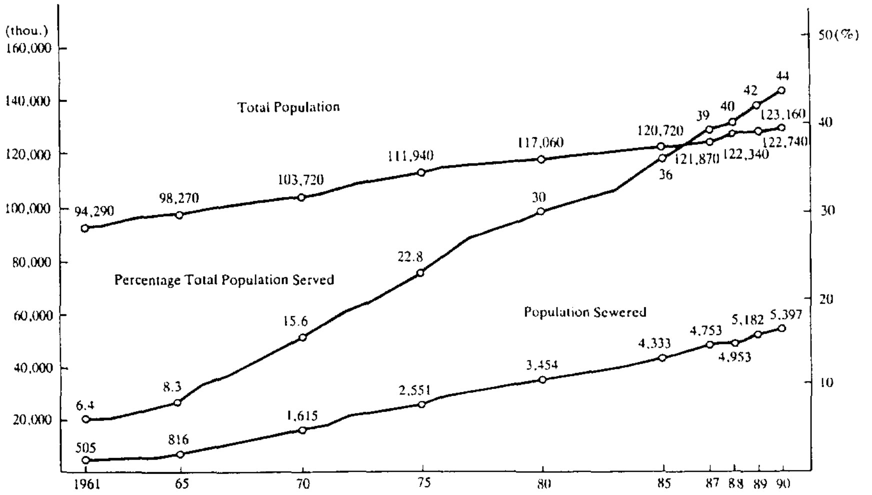

Fig. 1. Population served by sewers (1961–1990).

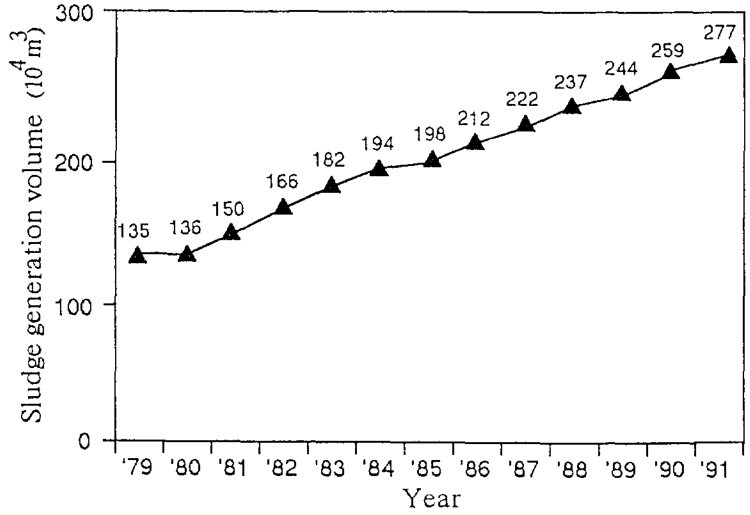

Fig. 2. Change of sludge generation volume (1979–1991).

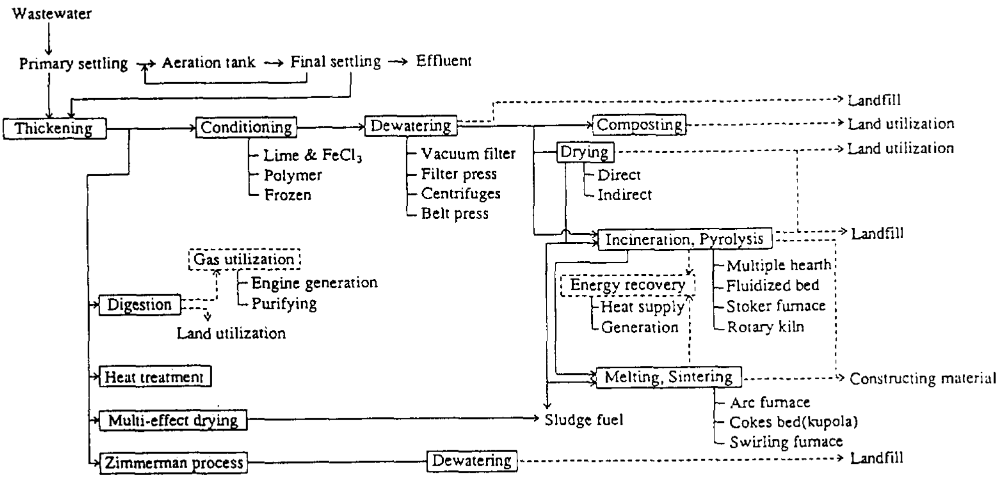

Fig. 3 Sewage sludge treatment system.

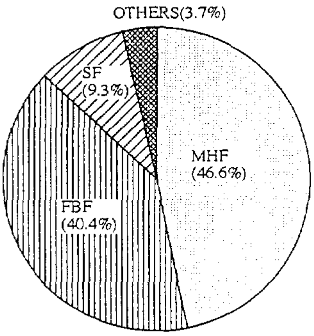

Fig. 4. The recent proportion of furnace type. (MHF = Multiple Hearth Furnace, FBF = Fluidized Bed Furnace, SF = Stoker Furnace)

OBJECTIVES OF THERMAL PROCESSING

The objectives of thermal sludge processing are (1) volume and weight reduction, (2) stabilization, (3) detoxification, and (4) reuse. Figure 5 shows how sludge weight and volume are reduced by thermal processing: drying, incineration and melting (Shimizu *et al.*, 1991). Incineration or melting processes decompose the organic portion of sewage sludge so that the resulting ash or slag is finally stabilized and does not decompose anymore to generate odor or polluted water problems. The melting process stabilized heavy metal content and stone-like slag may be reused as construction materials, etc.

TABLE 1. The Properties of Sewage Sludge

Chemicals Used		Lime	Polymer
Moisture (%)	Dewatered	79.0	81.7
	Dried	48.9	41.9
Ig-Loss (%·DS)		47.3	73.7
Elemental Compositon (%·DS)	H	4.07	5.18
	C	23.8	37.2
	N	2.32	2.76
	S	0.96	1.08
	Cl	0.70	0.24
	O	16.2	27.5
Higher Calorific Value (kcal/kg·DS)	Dewatered	2060	4100
	Dried	4360	5560
Lower Calorific Value (kcal/kg·DS)	Dewatered	90	200
	Dried	650	1930
Ash Composition (%)	Fe_2O_3	14.4	20.7
	CaO	37.9	6.76
	P_2O_5	4.34	10.2
	SiO_2	20.2	33.8
	MnO	1.30	2.26
	K_2O	0.75	1.75
	Al_2O_3	8.62	12.9
	MgO	2.09	3.49
	TiO_2	0.53	1.09
	Others	9.88	7.13

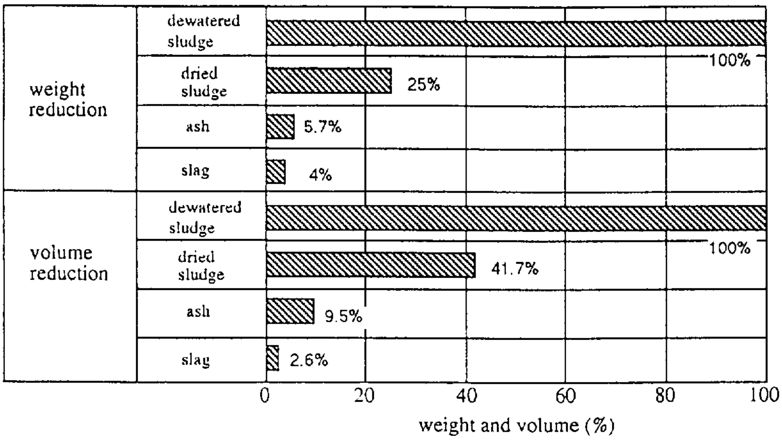

Fig. 5. Weight and volume reduction by thermal processing.

THERMAL PROCESSING TECHNOLOGY

Drying-Incineration System

The fuel oil consumption for sewage treatment amounts to 0.3 percent of the total national oil usage in Japan. The fuel is used as auxiliary fuel for sewage sludge incineration. The fuel oil consumption is reportedly 100 to 300 litre/ton of dewatered sludge for MHF (Multiple Hearth Furnace) and 100 to 500 litre/ton of dewatered sludge for FBF (Fluidized Bed Furnace). The key to reduce costs in the incineration process is to decrease the fuel oil consumption. The drying-incineration process with waste heat recovery was considered to be an energy efficient system compared with direct incineration. The authors built an energy balance model of the drying-incineraton system and studied the critical design parameters for energy optimization (Sakai *et al.*, 1989). The Kobe East Sludge Center was constructed based on this study and the drying-incineration system has been operated successfully. The flow diagram of the system is shown in Figure 6.

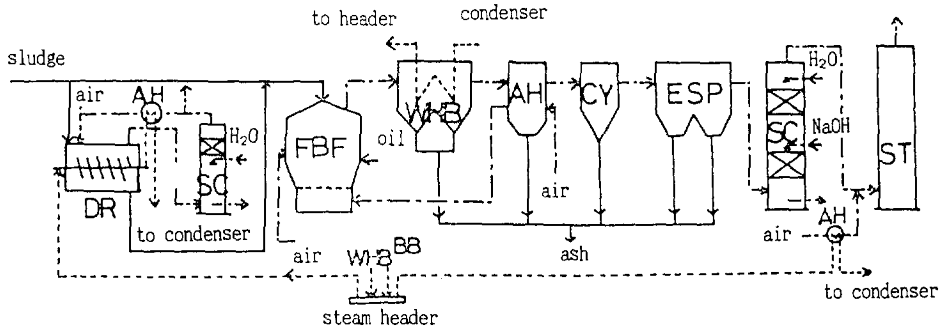

Fig. 6. Flow diagram of the drying-incineration system. (DR = dryer; FBF = Fluidized bed furnace; WHB = waste heat boiler; AH = air heater; CY = cyclone; ESP = electrostatic precipitator; SC = scrubber; ST = stack; BB = back-up boiler)

Sludge Melting System

There are five types of melting furnaces already developed and put to practical use for sewage sludge treatment; they are coke-bed melting furnace, reverbatory melting furnace, cyclone melting furnace, electric arc melting furnace, and microwave melting furnace. Figure 7 shows these furnaces. Either dewatered sludge or ash is fed into the furnace. Plasma torch melting has recently been developed mainly for ash melting. How to choose the proper melting system depends on the type of furnace, characteristics of sludge etc. Frequently sewage sludge is dried before feeding it to the furnace. Table 2 is a list of the commercial and demonstration plants in Japan. Here three types of melting system will be mentioned. The author participated significantly in their development.

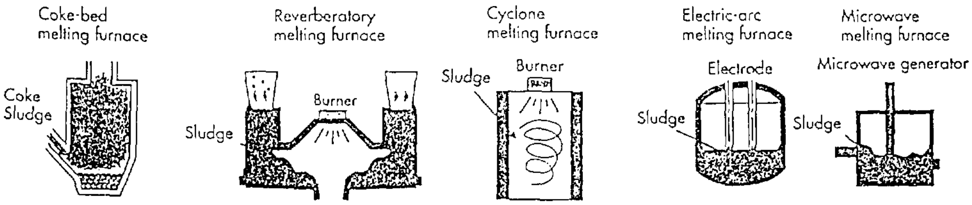

Fig. 7. Types of melting furnaces.

Coke-Bed Melting System

The authors firstly developed the coke-bed melting furnace (Yakeda *et al.*, 1989 & Sakai *et al.*, 1990). The core of the coke-bed melting furnace is an application of the cupola melting technology which has been used to manufacture cast metal. The cupola is a furnace in which ore and coke are melted in air. It is a cylindrical and vertical furnace of quite simple structure, having tuyeres for feeding air and a tapping hole at the bottom for discharging molten slag. To treat sewage sludge in the melting furnace, only ore should be replaced by sludge. A fixed amount of coke carbon is burnt inside the coke bed with primary air, generating high temperature exhaust gas. The exhaust gas gives part of its enthalpy to sewage sludge, and the drying and decomposition processes of sewage sludge proceed on the coke bed. The decomposition process converts the organic portion of sewage sludge into combustible gases. The combustible gases are, at the next stage, burnt out in the secondary combustion zone with secondary air. The inorganic portion of the sludge is melted in the high-temperature atmosphere of the coke bed forming molten slag, which flows down through the coke particles to be discharged continuously from a tapping hole.

TABLE 2. Melting Systems in Japan

	Type	Capacity	Slag Production in 1990	Started in
COMMERCIAL PLANTS				
Kase (Kawasaki)	Electric-arc	12.8 T-DS*/D	752 T/Y	1981
Cyuo (Chiba)	Swirling	15 T/D	279 T/Y	1987
Futakami (Toyama)	Reverberatory	5.3 T-DS/D 12 T-DS/D	235 T/Y	1988 1994
Western Hyogo	Coke-bed	40 T-DS/D ×2 40 T-DS/D	8,532 T/Y	1989 1993
North-East Osaka	Coke-bed	10 T-DS/D ×2	929 T/Y	1989
Aigawa-Cyuo (Osaka Pref.)	Coke-bed	70 T/D 110 T/D	1,194 T/Y	1990 1995
Konan-Cyubu (Shiga Pref.)	Swirling	40 T/D	1,042 T/Y	1990
Private Co.	Swirling	3 T-DS/D		1990
Southern Osaka	Reverberatory	25 T-DS/D ×2 12.5 T-DS/D	1,018 T/Y	1990 1991
Nanbu (Tokyo)	Swirling	160 T/D		1991
Toba (Kyoto)	Swirling	150 T/D		1995
DEMONSTRATION PLANTS				
Onoue (Kakogawa)	Swirling	50 T/D	1,064 T/Y	1987
Hokubu II (Yokohama)	Swirling	15 T/D		1989
Nakajima (Toyohashi)	Swirling	15 T/D		1992

* DS; dry solids

A flow diagram of the sludge melting system with coke-bed furnace, which was constructed in the Western Hyogo ACE Center, is shown in Figure 8. The dewatered sludge is dried to around 45 percent moisture content by an indirect-heating type steam dryer. The dried sludge is supplied to the melting furnace along with coke and a basicity adjusting agent. These are fed onto the upper part of the coke-bed. A basicity, defined as the weight ratio of calcium oxide to silicone oxides, near one is preferable from the standpoint of the fluidity of molten slag. Combustion air for the sludge and coke is fed at multi-stages as primary and secondary air for the controlled combustion with nitrogen oxides reduction. The nitrogen oxides concentrations are reduced as a result of changing the upper burning zone of the coke-bed to a reductive atmosphere and accelerating ammonia-denitrification in the furnace. The primary air for burning coke is supplied after being preheated by exhaust gas in the heat exchanger. The vaporization of the moisture contained in the sludge, and the gasification of combustible portion of sludge, proceed in the upper part of the coke-bed by getting heat from the high temperature exhaust gas passing through the coke-bed. The combustible gases from the sludge are completely burnt out in the furnace with secondary air. The coke-bed plays the role of fire grate and forms the stable high temperature zone above 1,600°C required for melting. The ash in the sludge moves downward and melts in the coke-bed and flows down among the coke grains and finally reaches the slag outlet.

The upper opening in the melting furnace is the secondary combustion zone for the combustion gas. It also serves to prevent the scattering of dust and to reduce the nitrogen oxides concentrations by maintaining a reducing two-step combustion atmosphere. By inserting a water pipe unit, the temperature of this space is kept at a temperature lower than the softening point of sludge ash, and waste heat is recovered as steam. The exhaust gas temperature from the furnace is kept at around 900 deg.C. The heat of the exhaust gas coming from the furnace is recovered by a waste heat boiler as steam, which is used for drying dewatered sludge and electric power generation. The exhaust gas from the boiler is introduced to an air pollution control unit which consists of a dry type electrostatic precipitator, a NOx reduction reactor, an alkali scrubber, and a wet type electrostatic precipitator.

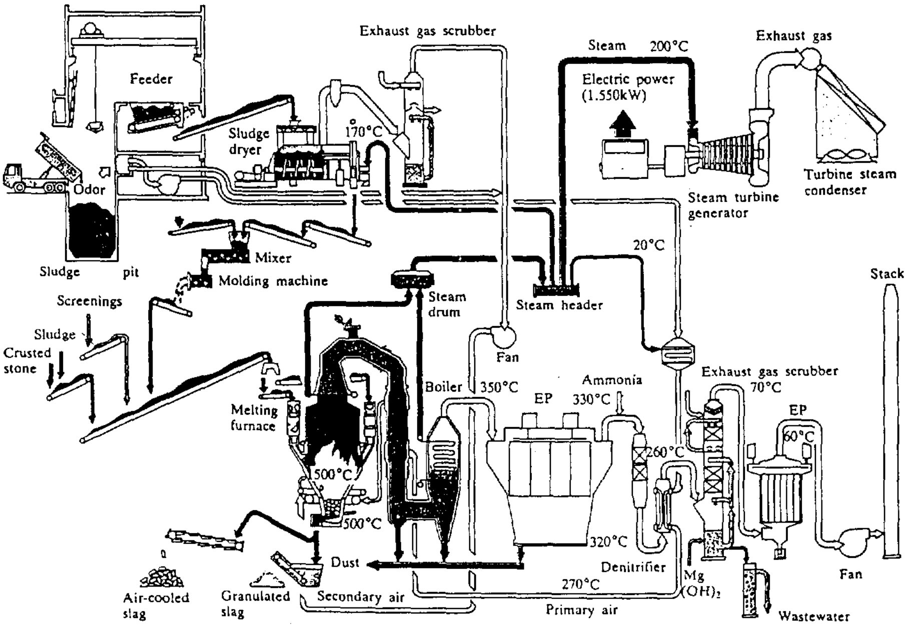

Fig. 8. Flow diagram of the sludge melting system with the coke-bed furnace.

Reverberatory Melting System

The reverberatory melting furnace is a vertically rotating type furnace which consists of a stationary inner cylinder and a rotating outer cylinder. The inner and outer cylinders form the primary combustion chamber. The dried sludge is fed into the furnace from a feed hopper. The rotation of the outer cylinder ensures constant feeding dried sludge around the full circumference of the primary combustion chamber. The feeding capacity can be varied by adjusting the vertical position of the inner cylinder. The fed sludge piles up in the primary combustion chamber and the chamber assumes a conical shape. The angle of the cone formed by the sludge is decomposed, incinerated and melted in the primary combustion chamber whose temperature is kept at about 1,300°C by the combustion of the organic portion of sludge and auxiliary fuel. The molten slag drops out from a slag port at the bottom of the primary combustion chamber. The combustion gas from the primary chamber is burnt in the secondary combustion chamber.

A flow diagram of the sludge melting system with reverbaratory melting furnace, which was constructed in the Osaka Southern ACE Center, is shown in Figure 9. The dewatered sludge is dried by indirect heating type steam dryers to a moisture content of approximately 20 percent. The dryer exhaust gas is recycled as carrier gas from the secondary combustion chamber is around 1,150°C. The heat is recovered by a waste heat boiler. The exhaust gas is cooled down to a temperature of around 230°C, and introduced into the air pollution control unit which consists of an alkali scrubber and a wet-type electrostatic precipitator.

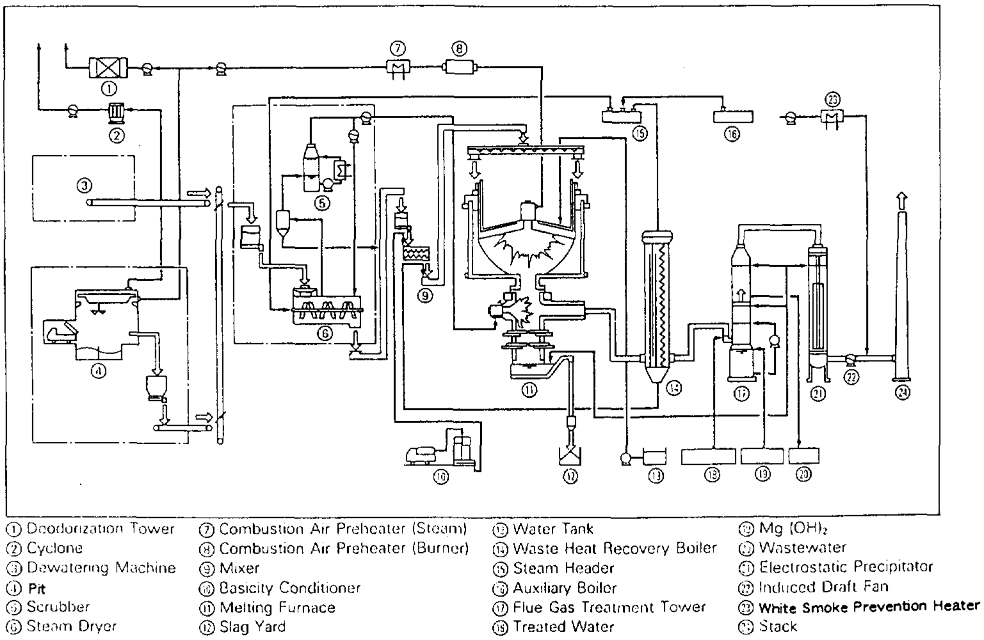

Fig. 9. Flow diagram of the sludge melting system with reverberatory melting furnace.

Swirling Flow Melting Systems

The swirling flow melting systems fall into two broad categories: ash melting system and dried sludge melting system. The particle size should be small (e.g. less than 50 micrometre) and the moisture content should be low (e.g. less than 10 percent) to keep the slagging conditions in the swirling type melting furnace. The system mentioned here has been developed on the basis of the pulverized coal combustion technology in the iron and steel making processes. Instead of drying, dewatered sludge is decomposed in the reduction atmosphere of a fluidized bed furnace and the decomposed residue is collected in a cyclone. The residue has a heating value of 100-300 kcal/kg due to the remaining fixed carbon contained in the sludge. The residue from the cyclone is fed into a swirling flow melting furnace shown in Figure 10. The exhaust gases from the cyclone and from the melting furnace are introduced into a secondary combustion chamber to be completely burnt. This system succeeded in eliminating the drying and pulverizing processes which require a large amount of energy (Oku *et al.*, 1990).

Characteristics of slag from the melting system

Three slag cooling methods have been developed and the shapes and physical properties of the slag depend on the cooling method as shown in Table 3. The strengths of slag itself and of concrete using slag are dependent on the degree of crystallization. Slag with a high silicon content and low basicity does not crystallize easily (Ohshima *et al.*, 1991).

Effective Utilization of Slag

Slag produced from sewage sludge can be used as road sub-base material, sand drain material and sand pile material. Secondary concrete products, like interlocking blocks, are made from concrete using slag as aggregate. Slag from sludge is being marketed. Osaka Prefectural Government constructed a secondary slag processing plant which consisted of a crusher, a vibrational screen and a magnetic separator to adjust the particle size and to remove ferrous materials. The government started to sell the "slag-stone" at a price of Y440/ton (approx. $4/ton) as road sub-base material (3–40 mm), aggregate (2.5–3 mm) for interlocking block and raw materials (<2.5 mm), and for manufacturing anti-skid tapes and paints. they plan to sell about 1,400 tons of slag per year.

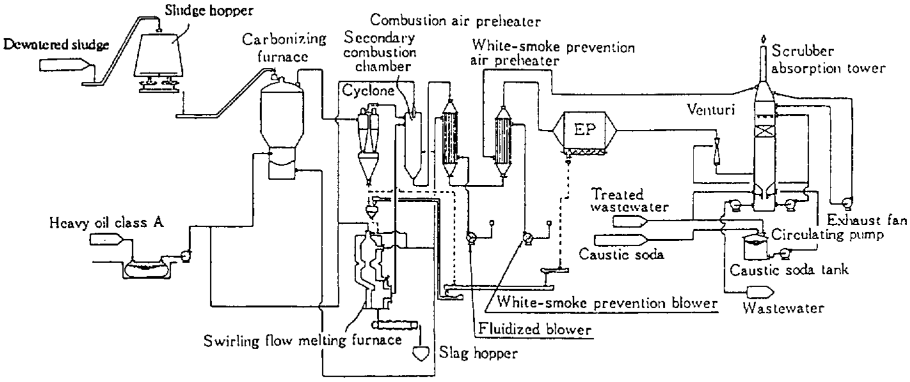

Fig. 10. Flow diagram of the sludge melting system with swirling flow melting furnace.

TABLE 3. Classification of Slag by Cooling Method

Slag type	Cooling method	Slag characteristics
Water-ground	Cooled by water	Vitreous, fine-grained
Air-cooled	Cooled by air	Vitreous, massive or crashed
Crystallized	Cooled by air temperature controlled reheated	Crystallized, massive or crashed

SUMMARY

The shortage of land, especially the difficulty of getting landfill sites, the rapid growth of urban areas, and stringent regulations against pollution facilitated the development of thermal processing of solid waste in Japan. The drying-incineration with heat recovery and melting systems are the representative technologies which are effective in densely populated urban areas.

REFERENCES

Hiraoka, M., Takeda, N., Sakai, S. (1988). Treatment and Sidposal of Solid Waste and Sludge in Japan, Consiglio Nazionale Delle Richereche

Hiraoka, M., Takeda, N., (1977). Behaviour of Hazardous Substances in Stabilization and Solidification Processes of Industrial Wastes, Toxic and Hazardous Waste Disposal Vol.3 (ANN ARBOUR SCIENCE), Chapter 11, pp. 107-124

Shimizu, K., Hasegawa, T. (1991). The Present Sewage Sludge Melting Treatment in Japan. The 4th KAIST-KYOTO UNIVERSITY Joint Seminar/Workshop on Civil Engineering,

Sakai, S., Hiraoka, M., Takeda, N., Ohhama, I. (1989). System Design and Full-scale Plant Study on a Drying-incineration System for Sewage Sludge, Water Science & Technology, Vol.21, No. 10/11, pp. 1453-1466

Takeda, N., Hiraoka, M., Sakai, S., Kitai, K., Tsunemi, T. (1989). Sewage Sludge Melting Process by Coke-bed Furnace: System Development and Application, Water Science & Technology, Vol. 21, pp. 925-935

Sakai, S., Hiraoka, M., Takeda, N., Tsunemi, T. (1990). Sewage Sludge Melting Process: Preliminary System Design and Full-scale Plant Study, Water Science & Technology, Vol.22, No.12, pp 329-338

Oku, S., Kasai, T., Hiraoka, M., Takeda, N. (1990). Melting System for Sewage Sludge, Water Science & Technology, Vol.22, No.12, pp. 319-327

Ohshima, Y., Masuta, T. (June 1991) Sludge Melting: Japan's Method of Treatment, Water Environment & Technology, pp. 68-71