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Reuse Technology for Slag Generated from Municipal Solid Waste Melting Systems†

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Abstract:

JFE Engineering has developed a direct melting system for municipal solid waste (MSW) and two types of MSW ash melting systems. Slag generated from the systems complied with the new safety quality requirements in the Japanese Industrial Standards (JIS). For application as road construction material, field tests were performed using air-cooled slag produced from the JFE electric-resistance ash melting furnace mixed with other construction materials and the slag-mixture reuse materials were dug up after about three years of use. The results showed that performance in construction work was almost the same as that of using normal materials without slag. Also, interlocking blocks and hollow concrete blocks were manufactured using the air-cooled slag mixtures. The prototypes had sufficient strength qualities as defined in the standards for concrete products. Moreover, water-cooled slag produced from the JFE high-temperature gasifying and direct melting furnace, which satisfies the FM2.5 standard for fine aggregate in road construction materials, was experimentally used in construction work as ground material around sewer water pipes. It was found that the slag material was fully suitable for this application.

1. Introduction

JFE Engineering has developed and commercialized various municipal solid waste melting systems to meet the need for volume reduction and reuse of residues generated from waste material processing plants. Moreover, the company has long been engaged in research and development of technologies for effectively using slag generated from the melting systems. Typical examples are described in this paper.

2. Melting Systems and Slag Manufacturing Technology of JFE Engineering

2.1 Melting Systems

JFE Engineering owns various imported and internally developed melting system technologies, which the former NKK and Kawasaki Steel were marketing independently, and which are now proposed to customers as optimal systems to satisfy their needs.

JFE's shaft-type high-temperature gasifying and direct melting furnace has been commercialized as a municipal solid waste direct melting system.

Two methods of the ash melting system in which melt ash from incinerators, such as the stoker type have been supplied to the market. One is the electric-resistance ash melting furnace employing a Joule heating method using graphite electrodes and the other is a plasma-type ash melting furnace employing a transfer-type plasma system using metal torches.

Furthermore, a next-generation stoker furnace that is directly connected to a rotary-kiln ash melting furnace has also been developed.

In addition to the aforementioned ash melting furnaces developed by other companies such as a rotary-type surface ash melting furnace, a coke-bed-type ash melting furnace and arc-type ash melting furnace have also been supplied to customers with JFE's stoker furnaces in response to their request.

2.2 Safety Quality of Slag

Common safety quality standards for slag have been issued for both road and concrete applications in the form of the following Japanese Industrial Standards (JIS)

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for slag produced from melting systems:

JIS A 5031: 2006 (Slag aggregate used for concrete by melting and solidifying general waste, sewage sludge and their incinerated ash)

JIS A 5032: 2006 (Slag used for roads by melting and solidifying general waste, sewage sludge and their incinerated ash)

The slag produced from melting systems supplied by JFE Engineering has the required safety quality for satisfying elution standards for hazardous materials and content standards for hazardous materials as shown in **Table 1**[1).

2.3 Slag Production Technology

2.3.1 Slag cooling technology

Slag cooling technology suitable for each melting system is used to produce slag. A water granulation method that enables simultaneous discharge and cooling of molten slag and molten metal is used in the high-temperature gasifying and direct melting furnace equipped with continuous slag discharge operation.

For the plasma type ash melting furnace, a tilting vessel method is used to discharge hot metal and slag to secure safe operation during discharge and a water granulation method is used to discharge metal separately from slag. For the electric-resistance ash melting furnace gravity separation in the melting furnace is used, and slag and metal are discharged from different ports. The slag cooling method can be chosen from among water granulation, air-cooling or indirect cooling depending on the application, and all of these methods produce high-quality slag.

Each method is outlined below.

(1) Water Granulation Method

This method is used to granulate molten slag to sandy form by injection into a water pool. Extensive experience and know-how in steelmaking is used for applying the design technology for optimizing the cooling water volume and shape of the water granulation pool and the dispersing technology for slag flow at the cooling section depending on with or without molten metal.

(2) Air Cooling Method

This technology is used to cool slag that has been separated from metals and discharged from the furnace on an air-cooling conveyor equipped with contiguous molds. Thick molten slag in the molds solidifies into a fist-size product due to cracking by shrinkage. It is then adjusted to the target granular size by using a crusher and a sieve. This slag has higher strength than water-granulation slag with larger granular size, and is suitable for roadbed material, etc.

(3) Indirect Cooling Method

This method is used to cool and solidify molten slag through contact with the surface of a water-cooled drum. Air-cooled slag can be obtained in the form of a thin sheet. It is possible to produce slag in the form of crushed sand that has higher strength than water-

Table 1 The safety quality example of JFE Environmental Solutions melting system

Item		Molten gasification system A Plant	Electrical resistance melt system C Plant	Plasma melting system D Plant	Standard value of JIS A 5031 JIS A 5032
Elution amount of hazardous (mg/*l*)	Cd	< 0.001	< 0.005	< 0.001	≤ 0.01
	Zn	< 0.005	< 0.005	< 0.001	≤ 0.01
	Cr^{+6}	< 0.005	< 0.04	< 0.005	≤ 0.05
	As	< 0.005	< 0.005	< 0.001	≤ 0.01
	T-Hg	< 0.000 1	< 0.000 5	< 0.000 5	≤ 0.005
	Se	< 0.005	< 0.005	< 0.001	≤ 0.01
	F	< 0.1	—	< 0.05	≤ 0.5
	B	< 0.1	—	< 0.1	≤ 1.0
Hazardous material content (mg/*l*)	Cd	< 1	< 1	< 0.05	≤ 150
	Zn	5	< 5	23	≤ 150
	Cr^{+6}	< 1	< 5	< 2	≤ 250
	As	< 5	< 5	< 5	≤ 150
	T-Hg	< 1	< 0.05	< 0.01	≤ 15
	Se	<10	< 5	< 1	≤ 150
	F	< 5	120	—	≤4 000
	B	85	140	—	≤4 000

cooled slag by applying light crushing. The benefits include simplification of equipment around the furnace than the air cooling method. and eliminating the water treatment process required in the water granulation system.

2.3.2 Adjusting physical properties to comply with standards

Slag quality standards are published according to application, such as for roads or concrete, by the establishment of JIS on slag produced from melting systems. Slag from the melting systems by JFE Engineering complies with the quality standards for the major basic characteristics (density, water content, etc.) and is individually prepared to comply with characteristics according to application (metal percentage, granular size, etc.).

For example, ferrous materials are removed by using magnetic separation if metal and slag are mixed together, and the aluminum is removed by using aluminum separation equipment (in the case of a surface melting furnace) if metal aluminum is mixed.

Slag of granular size is prepared first by removing coarse slag and then controlling the size according to the application by using a slag crushing machine and a sieve. Rounding treatment (elimination of corners) may also be applied to eliminate sharp corners by using a slag grinder.

3. Effective Application Technology for Slag from Melting Systems

3.1 Application as Roadbed Material[2–4)]

3.1.1 Material testing

Slag was prepared to meet C-40 standards by crushing, granular size adjustment and rounding treatment using air-cooled slag produced at a prototype facility using an electric-resistance ash melting furnace with 24 t/d processing capacity.

We mixed this C-40 air-cooled slag with regular recycled roadbed material (RM-40) as upper roadbed material, and RC-40 as underlying roadbed material, up to 50% on both.

Table 2 shows the results of indoor tests conducted on both the upper and underlying roadbed material. The compound slag showed a reduction in optimum water content and an increase in maximum dry density and corrected CBR value. (CBR: California Bearing Ratio is an index for the support strength of roadbed or roadway subgrade. Corrected CBR is the CBR value of roadbed or roadway subgrade that is solidified to 95% of its maximum dry density, which is an index used for the criteria of roadbed with pavement.) All plasticity indexes showed NP (NP means that the value was not measurable and satisfies the standard value.) for both with and without slag mixture, which satisfies the standards.

Table 2 Indoor test results of Roadbed material

Item		Upper roadbed material		
		Recycling roadbed material, RM-40	50% slag Mixture, C-40	Standard value
Optimum water content (%)		11.0	7.1	—
Maximum dry density (g/cm^3)		1.982	2.193	—
CBR values (%)	17 times	45	73	—
	42 times	102	127	—
	92 times	157	224	—
Corrected CBR** values (%)		95	108	≥80
Plasticity index (%)		NP*	NP	≤ 4
Item		Underlying roadbed material		
		Recycling roadbed material, RC-40	50% slag Mixture, C-40	Standard value
Optimum water content (%)		10.5	5.6	—
Maximum dry density (g/cm^3)		1.967	2.163	—
CBR values (%)	17 times	27	45	—
	42 times	75	99	—
	92 times	136	170	—
Corrected CBR values (%)		66	84	≥30
Plasticity index (%)		NP	NP	≤ 6

*NP: No measurements and its satisfy the standards
**CBR: California Bearing Ratio

Although the optimum asphalt quantity of asphalt mixtures compounded with slag becomes slightly less than that of normal compound material, its Marshal stability index fully satisfied the standards.

3.1.2 Experimental construction

Recycled dense-grade asphalt concrete was produced by compounding 15% of single granular size between 5 and 13 mm obtained by sieving C-40 slag with asphalt.

Test construction was conducted by compounding the above asphalt concrete with the aforementioned air-cooled slag and applying it to a public road in December 1995 (hereafter Construction District I) and in December 1996 (hereafter Construction District II).

Construction District I is a public road that has traffic volume L and measures 2.5 m wide and 40 m in length with a total area of 100 m^2, and it was divided into four zones. Underlying roadbed material, upper roadbed material or surface layer was each mixed with slag at three zones (Districts B, C, and D), respectively, and the fourth zone (District A) was constructed using regular recycled material (**Fig. 1**).

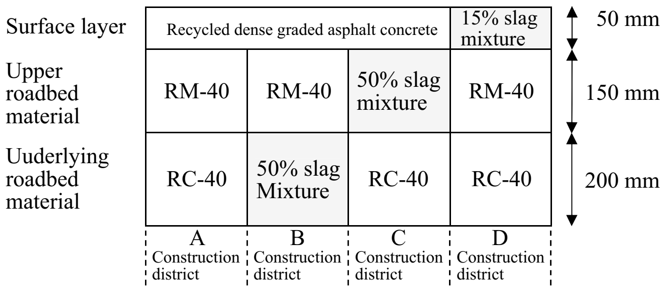

Fig. 1 Test construction pointless figure of Construction district I

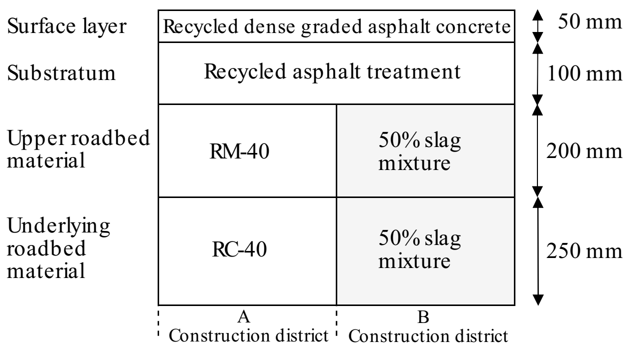

Fig. 2 Test construction pointless Figure of construction district II

Construction District II is a public road that has traffic volume B and measures 4.0 m wide and 120 m long with a total area of 480 m^2. Experimental construction was conducted using material mixed with air-cooled slag at the upper roadbed and underlying roadbed in one zone 4.0 m wide and 90 m long (District B). Another zone (District A) was constructed using regular recycled material (**Fig. 2**).

3.1.3 Results of experimental construction

Various follow-up studies were conducted for three years after the experimental construction. **Table 3** shows the change in cross-sectionally measured values of the road surface in Construction District I. Cross-sectionally measured values of road surface are used as an index to judge maintenance and repair requirements as established in the Road Maintenance and Repair Outline. There were no clear differences between District A

Table 3 Measured values shift of road surface cross section shape (Construction district I)

Types of mixture Upper/Surface layer Mid/Upper lying roadbed Lower/Underlying roadbed	Measurement position		Measured values (mm)				Variation from shortly after construction to 37 months after (mm)
			Shortly after construction	3 months after	15 months after	37 months after	
Recycled dense graded asphalt concrete RM-40 RC-40	A Construction district	1	1.5	1.5	1.5	1.0	−0.5
		2	4.0	4.0	5.0	4.5	0.5
		3	4.0	4.0	7.0	7.0	3.0
Recycled dense graded asphalt concrete Slag mixture RM-40 RC-40	B Construction district	1	4.5	4.5	5.5	5.5	1.0
		2	6.0	6.0	7.0	6.5	0.5
		3	4.0	4.0	4.0	5.0	1.0
Recycled dense graded asphalt concrete RM-40 Slag mixture RC-40	C Construction district	1	6.0	6.0	7.5	7.0	1.0
		2	2.5	3.0	4.0	3.0	0.5
		3	6.0	6.0	8.0	9.0	3.0
Slag mixture Recycled dense graded ssphalt concrete RM-40 RC-40	D Construction district	1	5.0	5.5	6.0	6.0	1.0
		2	1.5	1.0	3.0	2.5	1.0
		3	4.0	4.0	6.5	5.0	1.0

Table 4 Compounding test results of Slag mixtures for Reuse roadbed material(Construction district II)

Item		Underlying roadbed material		Upper roadbed material	
		50% slag Mixture RC-40	Standard value	50% slag Mixture RM-40	Standard value
Optimum water content (%)		7.0 (6.5)	—	7.8 (7.5)	—
Maximum dry density (g/cm³)		3.034 (2.028)	—	3.043 (2.033)	—
CBR values (%)	17 times	35 (32)	—	63 (65)	—
	42 times	70 (66)	—	98(96)	—
	92 times	110 (106)	—	120 (124)	—
Corrected CBR values (%)		65 (58)	≥30	82 (80)	≥80
Plasticity index (%)		NP	≤ 6	NP	≤ 4

In parentheses after the initial construction time

where regular material was used, and Districts B, C, and D where slag was mixed in. The change in value shortly after construction was relatively small, i.e., approximately 1–3 mm, and was far below the figure of 30–40 mm requiring maintenance and repair.

Sliding resistance value BPN (BPN: British Pendulum Number, which is recommended to be 40 or higher at a flat surface road) was 68 to 72 shortly after construction and gradually decreased to approximately 60 after 15 months. There were no differences in BPN between the construction districts with regular recycled dense asphalt concrete and that with 15% mixture of air-cooled slag.

After 37 months, there were no cracks or hairline-crack generation in any of the districts.

A follow-up study was conducted until 38 months after construction in District II, and cross-sectional shape, sliding resistance and crack propagation showed no effects from using the slag mixture.

3.1.4 Reuse test

Characteristics as reuse roadbed material were studied by digging up roadbed material from part of the test construction district. Constructed material was dug up 12 months after the construction at District I and 13 months after the construction at District II.

A compounding test on the dug-up roadbed material was conducted without size adjustment or mixture with the other materials, to simulate the future reuse.

Table 4 shows the results of the compounding test for RM-40 mixed with 50% slag of the dug-up material at Construction District II and RC-40 also mixed with 50% slag. The results are nearly the same as those for the compounding test at the initial construction period and they satisfy the standard values both in corrected CBR and plasticity index. Therefore, it was concluded that the material is suitable for reuse. The results of the reuse test at Construction District I were also the same.

Based on the above, it was confirmed that roadbed material using air-cooled slag could be used for application equivalent to regular material as roadbed material or asphalt mixture material.

3.1.5 Actual application of roadbed material in Yokohama City[4)]

Citizens, business owners and the municipal government of Yokohama have been working together to recycle and reduce the volume of waste, as well as pursuing resource-saving and recycling-based urban development following the "General Waste Processing Plan." An ash melting furnace was introduced at the Kanazawa Plant of the Environmental Division (currently Resource-Recycle Division) of Yokohama City as a "Resource-Recycle Type Waste Processing Facility" starting full-scale operation in April 2001 and the slag from the melting system is being used as roadbed construction material.

Slag produced at the Kanazawa Plant is supplied to a private recycling plant for paving material, as shown in **Fig. 3**. Slag complying with roadbed material standards (elution test, physical characteristics (granular size, strength)) is produced and shipped to be used by mixing with underlying roadbed material (RC-40).

Figure 4 shows a flow diagram of the slag processing equipment. Slag is crushed in a hammer-type crusher

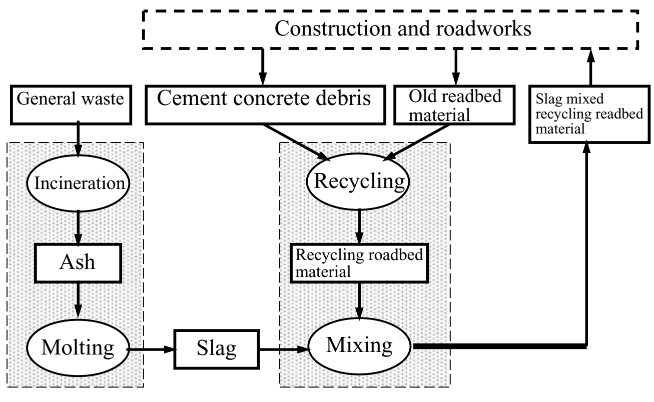

Fig. 3 Flow diagrams of effective use molten slag

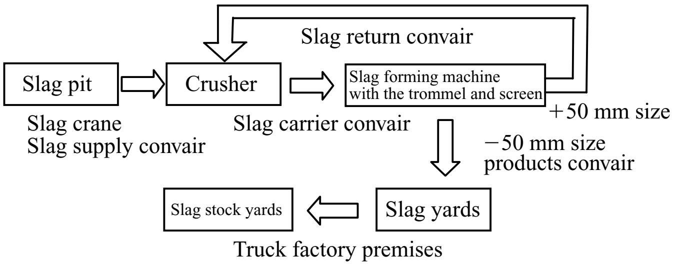

Fig. 4　Facility flow diagram of slag processing equipment

and rounded by a rotary-type slag-forming machine, then supplied as product.

Characteristics of slag produced by this process satisfy JIS for crusher-run stone 40–0 mm (C-40) by adjusting crushing/forming/granular size as shown in **Table 5**.

This slag has a larger diameter, higher corrected CBR value and relatively high strength due to the application of the air-cooled process.

3.2 Application as Aggregate for Secondary Concrete Products[5)]

3.2.1 Aggregate for interlocking blocks

Permeable interlocking block used for walkways and widely commercialized as landscaping material was produced in a conventional production process line as a trial run by entirely converting air-cooled slag obtained by crushing and adjusting the granular size to both fine and coarse aggregate under the mixing proportions shown in **Table 6**.

Table 7 shows the results of bending strength test and permeability test for permeable interlocking material mixed with slag.

No quality problems were observed even when using slag that was entirely converted to fine and coarse aggregate up to 81% of the total weight ratio. The permeability coefficient satisfied the standard number, which was above 0.01 cm/s. Furthermore, the Eco Mark label certified by the Japan Environmental Association was obtained for permeable interlocking blocks having slag

Table 5　Slag physical characteristics examples

Item		Measured values	Standard value	Remark	
Percentage Passing Sieve (Sieve Size, mm)	53	100.0%	100	①, ④	Crusher-run stone 40–0 mm (C-40)
	37.5	98.1%	95–100		
	19	67.8%	50– 80		
	4.75	18.5%	15– 40		
	2.36	11.5%	5– 25		
Abrasion loss		23.8%	≤50		Upper roadbed material
Absorption		0.64%	≤ 3.0		Surface layer · Substratum
Density in saturated surface-dry condition		2.628	≥ 2.45	②, ④	Surface layer · Substratum
Stability		4.1%	≤20	③, ④	Upper roadbed material
Corrected CBR values		83.0%	≥30	④	Underlying roadbed material

Remark number of ① – ④ is following next standers.
① JIS A 5001 (Crushed stone for road aggregate)
② JIS A 5015 (Iron and steel slag for road construction)
→JIS A 5032 (Melt-solidified slag material for road construction derired from municipal solid waste and sewage sluge)
③ JIS A 5005 (Crushed stone and manufactured sand for concrete)
→JIS A 5031 (Melt-solidified aggregate for concrete derived from municipal solid waste and sewage sludge)
④ Summary of asphalt concrete pavement (Crushed stone)

Table 6　Mix proportions of the prototype Interlocking

(kg/m^3)

Using material		Permeability A	Permeability B
Water		88	88
Cement	Portland blast-furnace slag cement. B species	400	—
	Ordinary portland cement	—	340
Silica fume		—	20
Blast-furnace slag		—	40
Fine aggregate	Slag	220	220
Coarse aggregate	Slag	1 896	1 900
Chemical admixture		4	4
Slag weight ratio (%)		81	81

Table 7　Bending strength of the prototype Interlocking

Type of interlocking	Age	Bending strength (N/mm^2)		Hydraulic conductivity (cm/s)	
Permeability A (81% slag mixture)	7 days	4.38	JASS7 Standard value ≥3.0	0.06	JASS7 Standard value ≥0.01
	6 months	4.18			
Permeability B (81% slag mixture)	7 days	3.72		0.013	
	6 months	3.85			

JASS: Japanese Architectual Standard Specification

Table 8 Mix proportion of the prototype Concrete hollow blocks

Using material	Compounding amount (kg)	Blending ratio (%)
Cement	330	11.2
Sand slag	400	13.6
Powder slag	300	10.2
Crushed sand	1 000	34.1
River sand	250	8.5
Pumice	650	22.2
Total	2 930	100

Table 9 Bending strength of the prototype concrete hollow blocks (23.8% slag mixture)

	Test results	Standard value
Maximum strength (kN)	39.2	—
Compressive strength (N/mm^2)	9.9	≥6

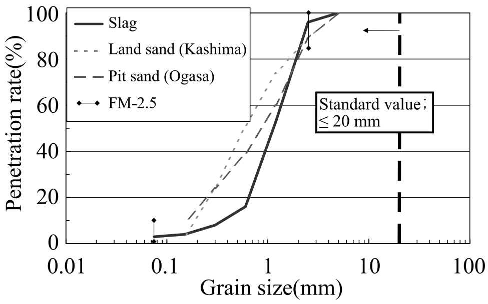

Fig. 5 Grain size frequency curve of slag

Table 10 Results of aggregate test

	Test results	JIS A 5032 Standard value
Absolutely oven-dry density (g/cm^3)	2.63	≥2.5
Water absorption (%)	0.56	≤3.0
Corrected CBR values (%)	34	—

content of 50% or higher.

3.2.2 Aggregate for hollow concrete blocks

Hollow concrete blocks were produced as a trial run by utilizing air-cooled slag obtained by crushing and adjusting granular size mixed to the given proportion shown in **Table 8** as aggregate. The blocks contain 23.8% slag consisting of 13.6% sand slag (equivalent to No. 7 crushing stones (5-2.5)) and 10.2% powder slag (equivalent to crushing sand (2.5-0)). This indicates that the equivalent of 26.9% aggregate except cement has been converted.

The prototype hollow blocks satisfied the required compressive strength, as shown in **Table 9**.

3.3 Application as Base Material for Sewage Water Pipes[6)]

3.3.1 Characteristics of base material for sewage water pipes using slag from melting systems

A total of 73 000 t/y of RDF (Refuse-Derived Fuel: Fuel utilizing waste material) that is transported from nine municipalities in Hiroshima Pref. is processed by melting, and the boiler steam is used for power generation at the Fukuyama Recycle Power Co. Slag produced in the melting process totals approximately 10 000 t/y and is entirely used as base material for sewage water pipes in Fukuyama City. **Figure 5** and **Table 10** show the size distribution of the slag and the results of physical properties tests on the slag, respectively. Although the slag produced from the melting systems is often much coarser than mountain sand, it satisfies the required standard value of less than or equal to 20 mm in size as base material for sewage water pipes and also complies with FM2.5 in JIS A 5032. The slag from the melting systems satisfies the standards specified for size distribution, absolute oven-dry density and water absorption in physical properties in JIS A 5032 stipulated for aggregate for road construction.

3.3.2 Experimental construction

To research the adaptability of the slag, which is from the Fukuyama Recycle Power Co., Ltd., as the base material for swage water pipes, comparison with the slag from blast furnace and study of the necessary consideration on the construction are carried out.

Photos 1 and **2** show work during the experimental construction and **Fig. 6** shows the results of experimental compacting work.

The following are the results obtained from the experimental construction:

(1) Material Characteristics
- (a) Physical characteristics and granular size of slag from the melting systems are almost the same as water granulation slag from a blast furnace.
- (b) Permeability is higher than that of water granulation slag from a blast furnace.

(2) Results of Construction
- (c) Compacting by water was possible, the same as sand during construction.
- (d) Sufficient compacting was accomplished by using a rolling compactor.
- (e) The slag was confirmed to be satisfactory for the base material for sewage water pipes.
- (f) Surface smoothing work was easier than that of water granulation slag from a blast furnace because of smaller specific weight.

(3) Necessary Future Considerations
- (g) Sufficient compaction by tamping is necessary

Photo 1 Experiment work (Work of first layer)

Photo 2 Experiment work (Hydraulic filling at second layer)

because the slag is not easily pushed around under the pipes compared to water granulation slag from a blast furnace.

The above results confirm that eco-slag using waste material can be satisfactorily used as base material for sewage water pipes.

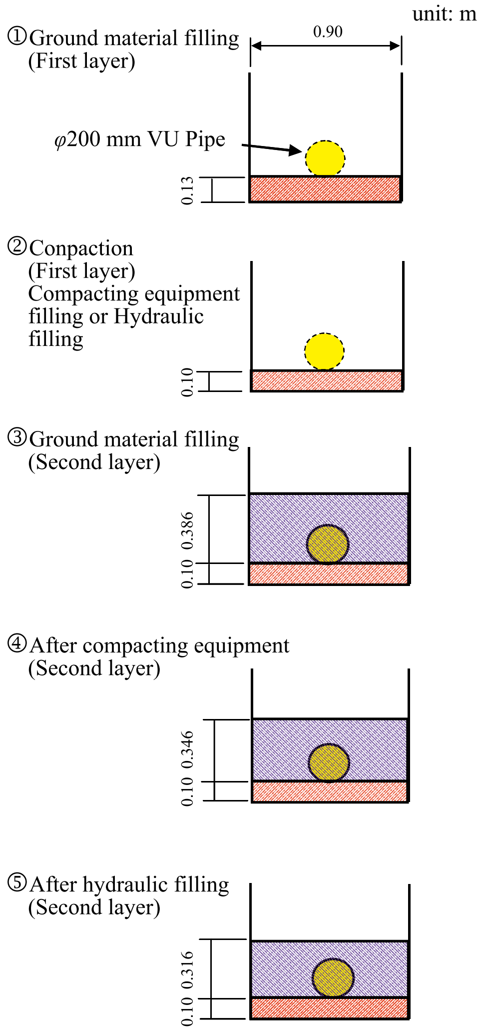

Fig. 6 Results of Compacting experiment work

4. Conclusion

Various slags produced from melting systems developed by JFE Engineering satisfy the quality standards set forth by JIS for the safety of slag products as introduced in this paper and also satisfy the standards for physical properties for the uses described here. This indicates that the slag can be fully and effectively used.

It is possible to minimize the final volume generated from waste material processing by fully utilizing the salg, by using the technology for recycling metal form the melting systems and by reducing the volume of molten fly ash from the waste melting process with non-ferrous smelting. Therefore, this technology can greatly help recycle resources in society. The technology for utilizing slag produced from the melting systems of JFE is expected to become widely used in the near future.

JFE Engineering express its gratitude to all parties involved from the municipalities and to those who used the slag during the process of developing the reuse technology.

References

1) Kojiya, Koji et al. "Slag quality produced in various melting systems." Proceedings of the 28th Japan Waste Management Conference. 2007, p. 165–167.
2) Nakamura, Yuko et al. "Evaluation of applicability of ash-melting slag as roadbed material." Conference Papers for the 9th Meeting of Japan Society of Waste Management Experts. 1998, p. 433–435.
3) Masuda, Toshio et al. "Long term utilization test of slag made from melting systems for roadbed material." Conference Papers for 12th Meeting of Japan Society of Waste Management Experts. 2001, p. 530–532.
4) Tomioka, Jun.; Yamanaka, Nobuyuki et al. "Operation status of electric-resistance ash-melting furnace at Kanazawa Plant of Environmental Division, Yokohama City." Proceedings of the 23rd Japan Waste Management Conference. 2002, p. 189–191.
5) Akashi, Tetsuo et al. "Reuse technology of slag made from ash melting system of municipal waste incineration." Proceedings of the 21st Japan Waste Management Conference. 2000, p. 151–153.
6) Sudo, Masahiro. "Applications of slag for sewage-pipe business area produced at a gasification and melting furnace." 2005 Eco-Slag Conference of the Japan Society of Industrial Machinery Manufacturers. 2005, p. 25–42.