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Separation and Recovery of Phosphorus from Steelmaking Slags with the Aid of a Strong Magnetic Field

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In order to make sure the great potential of steelmaking slag as a new phosphorus resource, domestic phosphorus material flow in Japan including iron and steel industry has been investigated based on the statistical data on 2002. It has been demonstrated that phosphorus in the steelmaking slag is almost equivalent with that in the imported phosphate rock in the view points of the amount and the concentration. Phosphorus exists mainly in the form of calcium-phosphate or its solid solution with calcium-silicate rather than the Fe_tO rich liquid phase in the slag and exhibits remarkable segregation in the solidified slag. If the strong magnetic field is applied to the crushed slag, precipitated calcium-phosphate solution phase can be separated from Fe_tO matrix phase due to the large difference of each magnetic property. It has also been indicated by the Waste Input–Output model that the phosphorus recovery from steelmaking slag by the new process proposed in the present work has great environmental and economical benefits.

KEY WORDS: steelmaking slag; phosphorus resource; calcium phosphate; dephosphorization; material flow analysis; fertilizer; input–output analysis.

1. Introduction

Phosphorus is a nutrient element that is essential for the growth of animals and plants, and is a substance that is essential for the production of fertilizers, in that phosphorus, together with nitrogen and potassium, is one of the three major elements present in fertilizers. The main raw material for industrial phosphorus is phosphate rock, 41.4 million tons of which were mined worldwide in 2000: the United States and Morocco account for 27% and 17.4%, respectively, of the world's total phosphate rock (phosphorus ore) production. Most of the phosphorus imported into Japan is in the form of phosphate rock and fertilizers, which can be broken down broadly into phosphate rock, ammonium phosphate (phosphorous fertilizer), and concentrated superphosphate. Since the United States stopped exporting phosphate rock in 1997 to conserve its own resources, the price of phosphate rock has been rising and Japan's total imports have been decreasing, as shown in **Fig. 1**.1)

In contrast to its nature as a strategic resource, as described above, phosphorus is one of the most detrimental impurities in steels, in that it reduces the low-temperature toughness of iron and steel products. Consequently, a thorough dephosphorization is made in hot-metal pretreatment and steelmaking processes, and therefore most of the phosphorus that is present in molten iron is eliminated into steelmaking slag. In other words, the dephosphorization process is a process by which the trace amounts of phosphorus present in raw materials such as iron ores and coke are concentrated into steelmaking slag. Like Thomas slag, for example, steelmaking slag has traditionally been utilized as a phosphorus fertilizer, and trials in Japan on the concentration, separation and recovery of phosphorus from slags have been reported.2–5) Although the significance of the separation and recovery of phosphorus from dephosphorization slag has been recognized, no effective method has yet been developed for this process. Currently, dephosphorization slag is utilized mainly in recycling to sintering processes aimed at recovering iron or as a building material for roads and other structures. If the separation and recovery of phosphorus from dephosphorization slag were to become technically feasible, this would have considerable ripple effects, as described later, in terms of, for example, securing a new phosphorus resource, mitigating problems associated with trace radioactive element contaminated in phosphate rock,6) effectively utilizing residues after phosphorus recovery, and drastically reducing the amounts of slag generated.

With this background, and by focusing on the difference in magnetic properties between crystalline phases present in steelmaking slag, we propose a method in which a strong magnetic field is used for the separation and recovery of

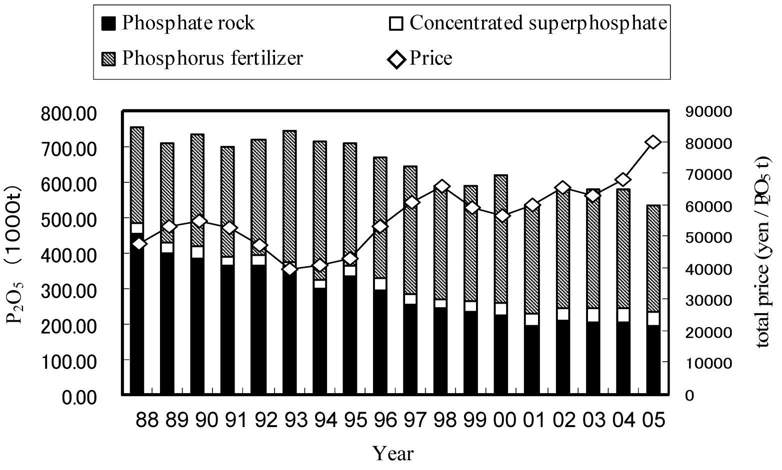

Fig. 1. Trends in the amounts and the prices of phosphorus resources imported into Japan.

crystalline phosphorus-containing phases from slag. The economic influences and environmental benefits of this method are also considered from the viewpoint of waste input–output analysis.

2. Phosphorus Material Flow in Japan

In general, it is important when developing an effective method for utilizing byproducts to have a quantitative grasp of the supply-and-demand relationship in the current economic system, or the material flow. However, preceding researches[7–9] on the domestic material flow of phosphorus do not take sufficient consideration of phosphorus flows originating from raw materials in the iron and steel industry. Accordingly, in our present study, we analyzed the domestic flow of phosphorus materials in Japan by examining various statistical data for FY2002, and we clarified the important role of steelmaking slag in the domestic flow of phosphorus material.

Since phosphorus hardly exists as the pure element and it circulates in society in a state of relatively low concentration, it is supplied by a variety of routes and is widely dispersed.[10] In the present study, we classify sources of phosphorus into three routes: the phosphate rock and fertilizer route; the food and feed route; and the iron and steel route. In relation to these three routes, the material flow for the phosphate rock and fertilizer route was assessed on the basis of Trade Statistics for Japan published by Ministry of Finance[1] and 2000 Input Output Tables published by Ministry of Internal Affairs and Communications.[11] For the food and feed route, the result of the analysis by Mizutani[7] were modified by using statistical data published by, among others, the Ministry of Agriculture, Forestry and Fisheries; the Ministry of Land, Infrastructure and Transport; and the Ministry of the Environment.[12–23] With respect to the iron and steel route, a material flow was derived from data published by the Nippon Slag Association,[24] together with various statistical data for iron and steel and for its related resources[25–30] and operating data for iron and steel companies. In the present study, we took into account 19 sectors, as shown in **Table 1**, in relation to the three routes for supplying phosphorus.

Table 1. Sectors for phosphorus material flow analysis.

Farm/Ranch	Soil accumulation	Chemical industry	Miscellaneous drainage
Food&Feed	Fertilizer	Steelmaking industry	River/coast area
Livestock	Products/by-products	Other industry	Sludge
Human	Phosphate ore	Steel	Waste
Nature	Other mineral resources	Steelmaking Slag	

For the iron and steel route, classifications of steelmaking slags and their average phosphorus concentrations are listed in **Table 2**. The targets of the study were, in terms of the phosphorus-charging route, iron ore, reclaimed scrap, limestone, coals (including coke), and chemicals used in surface treatments given in working processes. In the coke making process, all the phosphorus present in the raw coal was assumed to remain in the coke produced. Among the phosphorus inputs to the iron and steel industry, calculated amounts of phosphate rock and fertilizer route were used for coals, limestone, and iron ore; the input of iron scrap was taken from the Handbook for Iron and Steel Statistics; and input from surface-treatment agents was calculated from reported results from manufacturers. Slag and crude steel, taken together, were considered as the sole routes for discharge of phosphorus from the iron and steel industry. Discharges associated with steels were calculated from the crude steel-production figures presented in the Handbook for Iron and Steel Statistics, by assuming an average phosphorus concentration of 0.01 % in steels.

Iron and steel slags can be divided broadly into blast furnace slag and steelmaking slag: the latter can be subdivided into hot-metal pretreatment slag, basic oxygen furnace (BOF) slag, and electric arc furnace (EAF) slag. Because phosphorus was considered not to be present in blast furnace slag for the sake of the present study, the calculations of phosphorus discharged in slag only took account of that present in steelmaking slag. Although compositions and specific discharge parameters are strongly dependent on local conditions, including operating conditions, the flow of phosphorus in steelmaking slag could be deduced, as shown in **Table 3**, through a combination of a field survey of several blast-furnace manufacturers and statistical data from the Nippon Slag Association[24] and another data source.[25]

Table 2. Classification of steelmaking slags.

Total 93.4 kt-P				
BOF slag		EAF slag	Hot metal pretreatment slag	
Slag A	Slag B	Slag C	Slag D	Slag E
without HM de-P	with HM de-P		de-Si/de-S slag	de-P slag
24.9 kt-P	29.0 kt-P	2.9 kt-P	2.7 kt-P	33.9 kt-P
(ave P_2O_5=3.0%)				(ave P_2O_5=5.0%)

Table 3. Calculation conditions for phosphorus material flow.

coal/coke		Iron ore		Lime	
consumption	62210 kt	consumption	113858 kt	consumption	22419 kt
%P in mass	0.05	%P in mass	0.06	%P in mass	0.01
steel scrap		EAF slag		crude steel	
input	38000 kt	emission	3467 kt	production	107745 kt
%P in mass	0.01	%P in mass	0.17	%P in mass	0.004

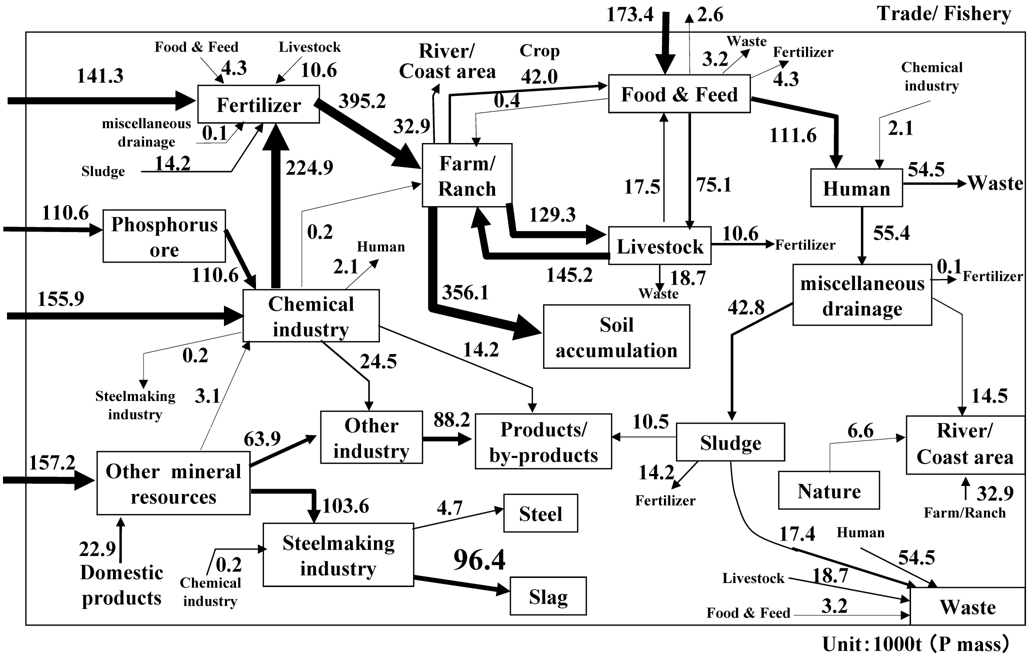

Fig. 2. The domestic material flow of phosphorus in Japan (2002).

The material flow of phosphorus in Japan is summarized in **Fig. 2**, based on the above results. The largest demand for phosphorus resource arises in the fertilizer-manufacturing sector, which is part of the chemical industry and which supplies approximately 400 000 tons of phosphorus to farmlands and ranches; this total comprises imports of 140 000 tons and inputs from the domestic chemical industry of 225 000 tons. Although a portion of this phosphorus circulates in the agriculture and livestock sector in the form of feed and livestock biomass, most is lost to the environment, including soils and rivers, or in wastes. At the extreme downstream of the material flow of phosphorus, the concentration of phosphorus is extremely low, of the order of ppm. If we consider that the concentration of phosphorus in ores as an industrial raw material is a little over 15%, it is apparent that phosphorus, whose main application is as a fertilizer, is an element with an extremely strong diffusivity.

The phosphorus input to the iron and steel industry was estimated to be 104 000 tons, approximately 90% of which, *i.e.* approximately 94 000 tons, becomes concentrated in steelmaking slag. Approximately 43 000 tons of additional phosphorus was calculated to become concentrated in drainage sludge: if this total is combined with that in steelmaking slag, the total exceeds the total amount of phosphorus imported as phosphate rock.

As described above, the origin of phosphorus circulation in the industrial field is import of raw materials such as ores, and the circulation is terminated in the environment, including rivers and soil, products, byproducts, and wastes. Among these, the phosphorus flow originating in other mineral resources has not been fully taken into account, and the flow of phosphorus included in products and byproducts occurring in product production processes has hardly been considered. We found from the estimation results of the present study that these flows are equivalent quantitatively to the domestic input of phosphorus in the form of imported phosphate rock. Phosphorus, in many cases, is present in small amounts in products and byproducts, and tends to diffuse finally into the environment. However, the phosphorus that is input into the iron and steel industry is guaranteed to be concentrated in steelmaking slag, and its location can be identified clearly. Much the same thing can be said about drainage sludge. However, steelmaking slag, as a source of phosphorus, has overwhelming advantages over drainage sludge in terms of water content and sensible heat when discharged (*i.e.*, the amount energy to be newly input for conversion of the waste into a phosphorus resource), and its phosphorus flow amount is two or more times that of drainage sludge. Consequently, steelmaking slag can be said to have considerable potential as a source of phosphorus.

3. Development of a Technique for Separation and Recovery of Phosphorus from Steelmaking Slag

3.1. Morphology of Phosphorus in Steelmaking Slag

Futatsuka *et al.*[31)] analyzed compositions of steelmaking slags (hot-metal pretreatment slags) produced by domestic blast-furnace manufacturers with an electron probe microanalyzer, with the aim of conducting a survey of the forms in which phosphorus exists in steelmaking slags after solidification. The results were presented in the form of a phase diagram for the $CaO–SiO_2–Fe_tO–P_2O_5$ system, and the equilibrium relationship between phases in which phosphorus is present was discussed. As a result, phases present in slag can be divided broadly into the following four categories.

Phase A: a phase in which phosphorus is concentrated at 10% or more, and which includes hardly any iron.
Phase B: a phase composed mainly of Ca and Si, which includes several percent of phosphorus and hardly any iron.
Phase C: a phase with a composition close to pure Fe_tO.
Phase D: a phase based on $CaO–SiO_2–Fe_tO$.

Phases A and B were considered to be either calcium phosphates $4CaO \cdot P_2O_5$ (C_4P) or $3CaO \cdot P_2O_5$ (C_3P) or solid solutions of these with calcium silicate $2CaO \cdot SiO_2$ (C_2S), and the slags were shown to have structures with these phosphorus-containing crystalline phases dispersed in $CaO–SiO_2–Fe_tO$-based matrices of Phases C and D. Futatsuka *et al.* reported that, although crystal grains of the phosphorus-containing phases and the matrix phases tend to be larger with slower cooling of the slag, the crystalline phases comprising the slags are basically the same.

According to the report of Futatsuka *et al.*, hot-metal pretreatment slag can be divided broadly into (1) crystalline phases that include phosphorus but not iron (Phases A and B) and (2) phases that include iron but not phosphorus (Phases C and D). In other words, crystalline phase groups (1) and (2) are complete opposites in terms of their contents of iron and phosphorus. We therefore believed that there was a high possibility that these phases could be separated magnetically by applying a strong magnetic field.

3.2. Magnetic Properties of Constituent Phases of Steelmaking Slags

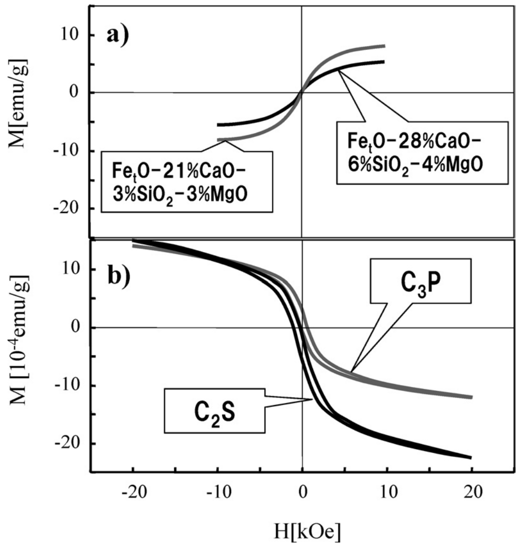

Fig. 3. The magnetization curves for an Fe_tO-based matrix phase (Phase D), calcium phosphate (Phase A), and calcium silicate (Phase B).

We measured the magnetic properties of C_3P, C_2S, and $Fe_tO–CaO–SiO_2$-based slag with a vibrating sample magnetometer (VSM) as part of a quantitative investigation of the possibility of magnetic separation of phosphorus-rich phases from slag. The results are shown in **Fig. 3** in terms of magnetization as a function of the magnetic field. The results shown in Fig. 3(a) are for two samples of phases with compositions equivalent to those of Phase D, which comprises the matrix phase of steelmaking slag. Figure 3(b) shows the results for commercially available C_3P powder and for C_2S compound powder synthesized from reagents of calcium carbonate and silicon dioxide (both produced by Kanto Chemical Co., Inc., special grade chemicals): these are crystalline phases that are similar to Phases A and B, respectively. In terms of magnetic properties, the phases shown in Fig. 3(a), which do not include phosphorus, are paramagnetic or ferromagnetic, and the phases shown in Fig. 3(b) which are C_3P (which contains phosphorus) and C_2S (which forms a solid solution with C_3P) are diamagnetic. In addition, the absolute values of magnetization of the phosphorus-containing phases are as little as 1/100th of those of the phases that do not contain phosphorus. Consequently, among steelmaking slags, the phases shown in Fig. 3(a), which are a matrix phases with nophosphorus, and the phases shown in Fig. 3(b), which contain phosphorus, show completely different behaviors in a magnetic field: we therefore found that it should be possible to separate these phases magnetically.

The phase that includes 4% P_2O_5 in the two crystalline forms shown in Fig. 3(a) has a magnetization of approximately 5 emu/g at 10 kOe, which is considered to be approximately saturated. We will now calculate the magnitude of the lateral movement of this phase for the case when it is allowed to fall 10 cm through a magnetic field with a 3-T horizontal magnetic strength and an approximately 35-T/m lateral magnetic field gradient.[32)]

The magnetic force is generally written in a vector expression as:

$$\vec{F} = \vec{\nabla}(\vec{M} \cdot \vec{H}) \text{ ....} (1)$$

where F is the magnetic force, M (Wb/m^2) is the magnetization, and H (A/m) is the magnetic field. For the sake of simplicity, we assume that the magnetic field is applied only in the lateral direction and we can then rewrite Eq. (1) as the one-dimensional Eq. (2).

$$F = \frac{M\,(\mathrm{Wb/m^2})}{\mu_0} \times \frac{\partial B}{\partial x} \text{ ....} (2)$$

where B is the flux density ($B=\mu_0 H$), and μ_0 is the magnetic permeability in a vacuum. M is considered to be saturated and therefore independent of the magnetic field. The strength of the magnetic field is set at $B=3.0\,\mathrm{Wb/m^2}=3.0\,\mathrm{T}$. The magnetic-field gradient ($\partial B/\partial x$) is set at 35 T/m,[33)] a value obtained from the external magnetic-field distribution for a commercially available 13-T superconducting magnet. Substitution of these values into the Eq. (2) gives a value of 175 N/kg for the magnetic force acting on a sample.

The time required by matter to freely fall by 10 cm is estimated at 0.143 s from Eq. (3)

$$x=1/2gt^2 \text{ ....} (3)$$

where g is the acceleration due to gravity (9.8 m/s^2) and t is the time. Because the acceleration caused by the lateral magnetic force is 175 m/s^2, the distance of lateral movement during the 0.143-s descent of the crystalline phase towards the magnet as a result of the magnetic force-induced acceleration of 175 m/s^2 is 179 cm.

The saturation value for the C_2S phase shown in Fig. 3(b) is assumed to be -0.0025 emu/g, by extrapolating the magnetization to 3 T (30 kOe). If we calculate the magnetic force for free fall under the same conditions as above, we find that the material is repulsed by the magnet with an acceleration of 0.9 m/s^2. Consequently, the crystalline phase containing phosphorus shifts its fall vector by approximately 0.9 cm toward the side opposite the magnet during a 10-cm fall.

From these results, we expected that the crystalline phases containing phosphorus would fall nearly vertically in a strong lateral magnetic field, whereas the slag matrix phases, which does not contain phosphorus, would either bend appreciably towards the magnet or would stick to the magnet: the two substances shown in Figs. 3(a) and 3(b) should therefore, in principle, be readily separable by a strong magnetic field of several teslas.

3.3. Magnetic Separation of Phosphorus from Steelmaking Slag

To verify whether the phosphorus recovery process from slag, as studied above, is actually feasible, we carried out a magnetic separation experiment using a strong magnetic-field generator of the superconducting bulk-magnet type,[33)] as shown in **Fig. 4**. The magnetic field strength on the surface of the bulk magnet was 2.2 T, and the magnetic field gradient measured with a Gaussmeter was approximately 1.1 T/cm. Approximately 1 g of the simulated slag described later was placed in a polyethylene cell (height 10 cm, width 7 cm, and depth 1 cm), which was vibrated horizontally between the bulk magnet surfaces with an amplitude of 3 cm for 3 min at a frequency of 30 cycles/min. This process should have resulted in a dynamic equilibrium between the magnetic force and gravity. The unmagnetized substance on the cell bottom and the magnetized substance were collected and analyzed.

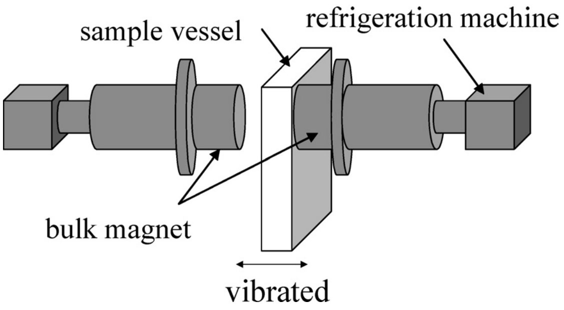

Fig. 4. Schematic of the experimental apparatus for magnetic separation.

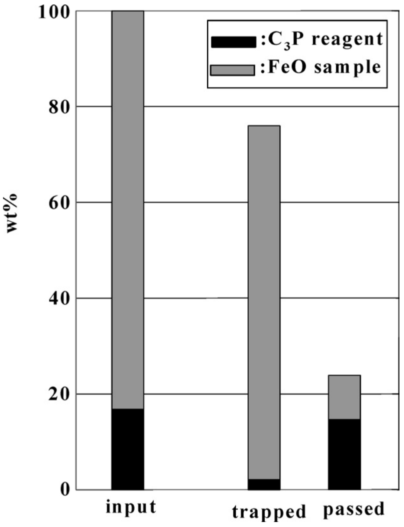

Fig. 5. Results for the magnetic separation of a mixture of Fe_tO and $3CaO \cdot P_2O_3$.

Table 4. Composition of slag used in the magnetic-separation experiment (in mass%).

T. Fe	CaO	SiO_2	Al_2O_3	MnO	P_2O_5
23.4	25.6	13.5	4.1	8.3	14.3

An initial experiment was carried out on a mixed powder of Fe_tO and C_3P chemicals. These had average grain sizes of 26 μm and 50 μm, respectively. To observe the effect of the magnetic field alone, avoiding aggregation of particles, fine SiO_2 powder (particle size: 90 nm) was added to the mixed sample at a rate of 1%. The results are shown in **Fig. 5**. Since more than 90% of the C_3P in the mixture was collected as unmagnetized substance in the 2-T magnetic field, the practical application of the magnetic separation method should be feasible.

Next, an experiment was carried out on a synthetic dephosphorized slag with the composition listed in **Table 4**. The slag was prepared as follows. After reagents were weighed at the aimed composition, the mixture was heated to 1 400°C in an argon atmosphere in an iron crucible. The material was then cooled slowly to room temperature at 1°C/min to grow-up the crystal size of the phosphorus-rich

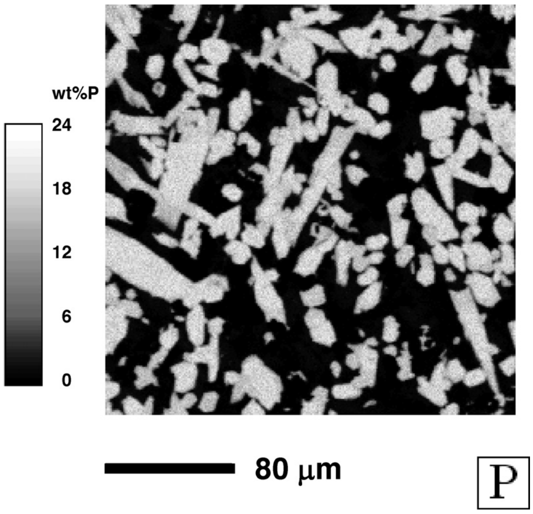

Fig. 6. Phosphorus mapping image of the slag used in the magnetic-separation experiment.

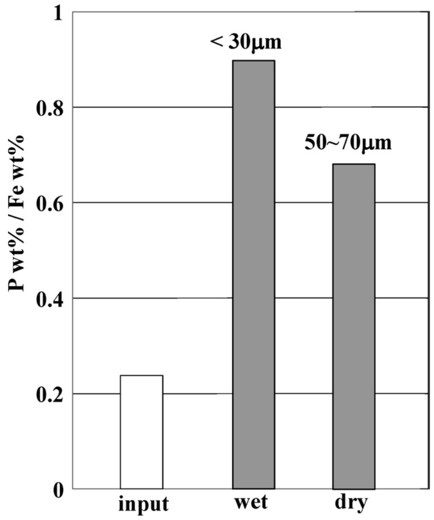

Fig. 7. Results for the magnetic separation of the dephosphorization slag.

phase. The resulting material, as shown by microscopic observation (**Fig. 6**), had an average grain size of Phase A or B of 70 μm. This slag was crushed in an agate mortar and used as an experimental sample. Two kinds of samples were prepared in terms of grain size: $<30\,\mu$m and 50–70 μm. Because the sample with a grain size of $<30\,\mu$m showed significant aggregation, leading to difficulties in efficient magnetic separation, 1 g of the sample was dispersed in approximately 20 mL of distilled water, and the experiment was carried out under the same conditions. In the case of the sample with a grain size of 50–70 μm, no significant aggregation was observed, so the experiment was conducted on the dry sample without using distilled water. The results are shown in **Fig. 7**. The phosphorus concentration in unmagnetized substance is indicated in the diagram by the mass ratio of phosphorus to iron in the analyzed sample. The results in Fig. 7 show that phosphorus was concentrated by a factor of 3–4, and approximately 50% of phosphorus in the initial slag was recovered.

We conclude from these results that the basic principle of the magnetic separation method has been established. The greatest challenge in scaling up the method to a practical level is how to coarsen the phosphorus-rich phases and matrix phases and convert them into independent particles. Consequently, detailed investigations of the effects of cooling conditions on the grain-size distributions of slag particles are required, together with studies of the effects of the magnetic-field gradient, the magnetic field strength, *etc.*

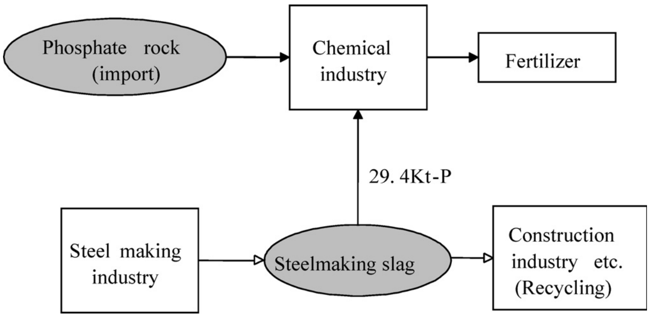

Fig. 8. Material flow between the chemical and steelmaking industries, based on the scenario.

4. Effects on the Environment and the Economy of Using Dephosphorization Slag as a Source of Phosphorus

On the assumption that phosphorus recovery from steelmaking slag by the present technique is feasible, we analyzed the economic spillover effects and the effects in reducing environmental loadings by using Waste Input–Output table (WIO).[34,35] **Figure 8** shows an outline of the scenario with phosphorus recovery from steelmaking slag set as an analysis target. A new flow for slag-recovered material as a raw material for phosphorous fertilizer going from the steelmaking industry to the chemical industry is placed between the two industries, which previously have had independent phosphorus flows. To analyze the spillover effect of this flow, the following six points were assumed in the phosphorus-recovery scenario.

1. To quantify the changes in materials flows in Japan as a whole resulting from the introduction of the new flow shown in Fig. 8, as a first-order approximation, the loadings necessary for heat treatment and crushing of slags, as well as those for the construction and operation of a magnetic-separation facility, are excluded from the objects examined.
2. Dephosphorization slags from hot-metal pretreatment and BOF slag, which among steelmaking slags have relatively high contents of phosphorus, were selected as the slags for treatment, and 50% of the phosphorus present in them was taken as being recoverable. Therefore, 29 000 tons of elemental phosphorus (approximately 0.5% of the total amount of steelmaking slag discharged) should be recoverable. The amount of slag discharged is reduced by the amount of phosphorus recovered, and hence the loading amount is reduced by this amount.
3. Phosphorus recovered from slag is charged into the chemical industry as a raw material for the production of fertilizer, *etc.*, and the import of phosphate rock is reduced by an amount equivalent to the charged amount. The transaction price for 1 ton of slag phos-

Table 5. The environmental and economic effects of recovery of phosphorus from steelmaking slag, estimated by the waste input–output model.

Industrial Sector (unit:one million yen)	Output (without P recovery)	Output (with P recovery)	Change rate (%)
Materials for ceramics	215,699	179,282	−16.883
Fertilizer	421,542	418,560	−0.707
Chemical products	25,396,046	25,342,342	−0.211
Coal products	856,933	855,529	−0.164
Steel making	20,138,980	20,116,761	−0.110
General machinary and equipment	28,735,191	28,641,034	−0.328
Electricity	16,847,969	16,823,987	−0.142
Water supply	2,894,636	2,888,204	−0.222

Environmental effects and others	Emissions and others (without P recovery)	Emissions and others (with P recovery)	Change rate (%)
Carbon dioxide emissions (t-C)	345,123,313	335,929,461	−2.664
Landfill consumption (m^3)	190,313,886	184,583,080	−3.011

phorus between the steelmaking and the chemical industries is set here as the same as that for the equivalent amount of phosphate rock yielding 1 ton of phosphorus.

4. All slag residues after phosphorus recovery are charged into the construction material sector as a material for building roads *etc.*, as is conventionally done.
5. The newly incurred loading arising from transportation between slag yards and chemical plants as a result of slag recovery is offset by the reduction in the amount of transportation of phosphate rock and can therefore be ignored.
6. Changes in the fertilizer-production process and increases and decreases in loading due to partial replacement of phosphate rock with slag as a raw material can be ignored.

The results of model calculations of changes in the amounts of domestic production and the occurrence of environmental loading arising from phosphorus recovery from slag are summarized in **Table 5**. The ripple effects of recovery of phosphorus from slag reach almost all industrial sectors, although this is understandably characteristic of an input–output model that describes the interdependence of domestic industries. In other words, phosphorus recovery from slag was predicted to affect 80 industrial sectors, and 13 of these sectors, including the ceramics raw-material sector and the chemical-fertilizer sector, show rates of change of 0.1% or more. It is found from the result shown in Table 5 that, as a result of reflection of influences of intersectorial transactions of phosphorus recovery from slag between the chemical industry and the steelmaking industry, production activities in the ceramic raw-material minerals sector and the chemical-fertilizer sector reduce substantially. Additionally, there are considerable effects on several industries, including steelmaking, chemical products, coal products, and general machinery and equipment as a result replacement of a considerable portion of phosphate rock input by materials recovered from steelmaking slags. On the other hand, the lower rows of Table 5 show significant reductions in generation of carbon dioxide gas and landfill consumption, so it is clear that replacement of phosphate rock with phosphorus recovered from slags considerably reduces environmental loadings.

However, with respect to the first of the six assumption listed above, there is an additional environmental load arising from the construction and operation of the facility, but, as stated in Assumption 4, the residues can be recycled to ironmaking and steelmaking processes, depending on the phosphorus recovery rate, suggesting there is a potential for reducing the overall environmental loading.

Although the scenario set in the present study is restricted and simplified, trial calculations of economic effects and environmental load-reducing effects resulting from the recovery of phosphorus from steelmaking slag carried out by using a WIO model showed that the present technology should have positive effects on both the economy and the environment. The technology should allow recycling of residues from phosphorus recovery to a sintering process and, in addition, should permit the use of iron ore with a higher phosphorus content, which is cheaper and present in larger deposits. Therefore, excellent results are expected in terms of economic benefits and reductions in environmental loading.

5. Conclusions

We conducted research with the aim of developing a technology for separating and recovering phosphorus from steelmaking slags by using a strong magnetic field, and we obtained the following conclusions.

We clarified the macro-domestic material flow phosphorus within Japan. The flow of phosphorus present in iron ore and coal, which had not previously been taken into consideration, was shown to be nearly equivalent in volume to the amount of phosphorus imported in the form of phosphate rock. In particular, the amount of phosphorus concentrated in steelmaking slags is equivalent to approximately 30% of the phosphorus consumed as a raw material for fertilizer and this is therefore worthy of notice as a target for phosphorus recovery.

A magnetic-separation method utilizing the difference in the magnetic properties between phosphorus-rich phases and matrix phases of steelmaking slag was proposed and validated experimentally. Experimental results confirmed the separation of phosphorus-rich phases from slag by a magnetic-field gradient of around 2 T, establishing the principle of magnetic separation.

Quantitative evaluations of economic effects and environmental load-reducing effects of the magnetic-separation of phosphate from steelmaking slags were conducted by using a waste input–output model, which confirmed the effectiveness and value of the method.

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REFERENCES

1) Trade Statistics of Japan, Ministry of Finance (2004); http://www.customs.go.jp/toukei/info/index.htm (accessed, 1, April, 2006)
2) H. Ono, A. Inagaki, T. Masui, Y. Narita, T. Mitsuo, S. Nosaka and S. Aida: *Tetsu-to-Hagané*, **66** (1980), 1317.
3) T. Fujita and I. Iwasaki: *Sci. Tech. Rep. Min. Coll. Akita Univ.*, **10** (1989), 15.
4) S. Shiomi, Y. Muraki and N. Sano: *Tetsu-to-Hagané*, **71** (1985), 1504.
5) H. Suito and M. Tokuda: *ISIJ Int.*, **35** (1995), 1079.
6) M. S. Al-Masri, S. Mamish and Y. Budeir: *J. Env. Radioactivity*, **58** (2002), 35.
7) J. Mizutani: *J. Jpn. Soc. Civ. Eng.*, **556** (1997), 103.
8) J. Ando and H. Otabe: *Saisei to Riyou (Recovery and Utilization)*, **14** (1991), 40.
9) F. Mishina and T. Shinpo: *Saisei to Riyou (Recovery and Utilization)*, **26** (2003), 13.
10) V. Smil: *Annu. Rev. Energy Env.*, **25** (2000) 53.
11) 2000 Input Output Tables, Ministry of Internal Affairs and Communications, Japan, (2004).
12) Ministry of Agriculture, Forestry and Fisheries, General Food Policy Bureau, Food Policy Planning Division, Planning Team: Food balance sheet, (2002); http://www.kanbou.maff.go.jp/www/fbs/fbs-top.htm (accessed, 1, April, 2006)
13) Science and Technology Agency, Resources Council (ed.): Standard Tables of Food Composition (Survey Report Concerning Revision of Standard Tables of Food Composition), Fifth Revised ed., (2000); http://food.tokyo.jst.go.jp/(accessed, 1, April, 2006)
14) Ministry of Agriculture, Forestry and Fisheries, Agricultural Production Bureau, Agricultural Materials Division (Supervised) and Association of Agriculture and Forestry Statistics: Pocket Fertilizer Catalogue, (2002/2003).
15) Ministry of Agriculture, Forestry and Fisheries, Agricultural Production Bureau, Livestock Industry Department, Livestock Production and Feed Division (Supervised) and Association of Agriculture and Forestry Statistics: Handbook of Circulating Feed, (2002).
16) Ministry of Agriculture, Forestry and Fisheries, Statistics Department (ed.) and Association of Agriculture and Forestry Statistics: Livestock Statistics, (2002); http://www.tdb.maff.go.jp/toukei/a02smenu?TouID=F009 (accessed, 1, April, 2006)
17) Web site of Ministry of Agriculture, Forestry and Fisheries, Agricultural Production Bureau, Livestock Industry Department, Livestock Industry Policy Planning Division, Livestock Industry Environment Policy Office: Situations surrounding livestock environment, http://www.maff.go.jp/chikukan/(accessed, 1, April, 2006)
18) Ministry of Land, Infrastructure and Transport, City and Regional Development Bureau, Sewerage and Wastewater Management Department: Database of effective utilization of sludge; http://www.mlit.go.jp/crd/city/sewerage/info/odeidb/031224db.html (accessed, 1, April, 2006)
19) Statistical data on the home page of Ministry of Land, Infrastructure and Transport, River Bureau: Normal discharge of Class A river system and flow regime of Class A river system, (2000); http://www.mlit.go.jp/river/jiten/toukei/index.html (accessed, 1, April, 2006)
20) Ministry of Land, Infrastructure and Transport, River Bureau (ed.) and Japan River Association: Annual Records of Water Flow, (2001).
21) Home page of Ministry of Land, Infrastructure and Transport for hydrological and water-quality database: Database of dams; http://www2.river.go.jp/dam/(accessed, 1, April, 2006)
22) Ministry of the Environment, Minister's Secretariat, Waste Management and Recycling Department, Waste Management Division: Waste treatment in Japan, (2004); http://www.env.go.jp/recycle/waste_tech/ippan/h13/data/disposal.doc (accessed, 1, April, 2006)
23) Web site of Statistics Bureau, Ministry of Internal Affairs and Communications: http://www.stat.go.jp/english/index.htm (accessed, 1, April, 2006)
24) Web site of Nippon Slag Association for statistical data: http://www.slg.jp/e/statistics-e.htm (accessed, 1, April, 2006)
25) Handbook of Iron and Steel Statistics, The Iron and Steel Federation of Japan, (2003).
26) Statistical data on the home page of Limestone Association of Japan: Transitions in limestone production volume and shipping volume by application; http://www.limestone.gr.jp/
27) Yearbook of Mineral Resources and Petroleum Products Statistics , Ministry of Economy, Trade and Industry, (2002); http://www.meti.go.jp/statistics/index.html (accessed, 1, April, 2006)
28) The Japan Institute of Energy (ed.): Coke Note 2004, (2004).
29) Web site of Japan Coal Energy Center: http://www.jcoal.or.jp/jcis/jcis.html (accessed, 1, April, 2006)
30) Web site of Nation. Inst. Env. Studies: Database on Chemical Substances; http://www.nies.go.jp/db/index.html#kenko (accessed, 1, April, 2006)
31) T. Futatsuka, K. Shitogiden, T. Miki, T. Nagasaka and M. Hino: *ISIJ Int.*, **44** (2004), 753.
32) K. Obara and H. Okada: *Bull. Iron Steel Inst. Jpn.*, **10** (2005), 402.
33) T. Oka, K. Yokoyama, Y. Itoh, Y. Yanagi, M. Yoshikawa, H. Ikuta, U. Mizutani, H. Okada and K. Noto: *Physica C*, **392–396** (2003), 709.
34) S. Nakamura and Y. Kondo: *J. Ind. Ecol.*, **6** (2002), 39.
35) K. Yokoyama, T. Nagasaka and S. Nakamura: *Bull. Iron Steel Inst. Jpn.*, **10** (2005), 862.