Geotechnical Applications of Industrial By-products for Reducing Environmental Impacts – In the Case of Pulverized Coal Fly Ashes -

by

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A B S T R A C T

Based on the results from investigation of behaviour of pulverized fly ashes (PFA) at laboratory and field, the way how to reduce the environmental impacts to geotechnical practices is considered and described. In order to reduce discharged industrial by-products, it should primarily be emphasized that an effort are made as much as possible not to put into burning. Secondarily, an effort must be made to increase amount of utilization to geotechnical engineering practices. In addition, from an environmental point of view, we should challenge to create innovative materials which are eligible for controlling other wastes and remedying contamination in soils by using industrial byproducts which belong to wastes. This is a new concept in which the polluting materials can be eliminated by making use of wastes. Based on the above-stated concept, the previous and possible utilization of PFA is classified into: (1) reclamation, embankment or backfill material, (2) light weight geo-material, (3) soil stabilization/improvement, and (4) environmental material. The reason why PFA, in particular, slurry PFA has been used and will possibly be used more widely is due to the fact that PFA has the advantages : (i) low specific gravity leading to a light weight geomaterial, (ii) high pozzolanic activity enhancing strength, especially due to cement addition, and (iii) spherical shape of particles producing isotropy and then pumpability. As well as the concept of reducing geo-environmental impacts, the present text mainly describes the successful results at laboratory and field which have been obtained by the authors. The most important issue in application of byproducts including PFA for geotechnical practices is to prevent leakage of polluted substances from sedimentary deposits, ground and earth structures. As one of possible techniques for achieving this purpose, a method of washing off the polluted substances by hot water is described.

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1 INTRODUCTION

More than 398 million tons of industrial wastes have annually been discharged in Japan. Although, because of the vast types and quantity of industrial wastes, the law for the Promotion of resources Recycling, being enacted from 1991 in Japan, has gradually been playing a role in promoting the utilization, more efforts are required to minimize environmental impacts. Geo-materials used for foundations and earth structures are expected to be a suitable target to increase waste utilization, because an enormous quantity of materials can be used in civil engineering practices. One issue that need to be addressed in relation to the low rate of utilization would be a lack of technical information exchange, especially of the chemical and mechanical properties in actual application.

Among the industrial wastes, ashes are counted as one of usable materials in civil engineering practice. Coal fly ash is a representative by-product obtained by combustion. In Japan, 10% of the total electrical power has been generated by pulverized coal combustion and is expected to increase up to 20% by 2001. A half of pulverized coal ash (PFA) being discharged from electrical power stations are utilized, in which 70% of PFA is used for the cement industry. Because of the limitation of cement production, the other usage is demanded for the future power plants. In this aspect, the utilization as geo-materials is promising. In fact, comprehensive studies have been carried out, for example, for the use in port, harbor and island construction projects. Besides these, PFA will possibly be used as geo-materials which can reduce environmental impacts, by eliminating the polluting substances. The present paper also refers to this possibility.

2 PHILOSOPHY OF REDUCTION OF GEOENVIROMENTAL IMPACTS

In order to reduce discharged industrial byproducts, it should primarily be emphasized that an effort and an attempt as much as possible are made not to put into burning. Secondarily, an effort must be made to increase the amount of utilization to geotechnical engineering practices as is shown in Fig. 2.1 and Fig. 2.2. In addition, from an environmental point of view, we should challenge to create innovative materials which are eligible to decrease production of wastes, and to control leachate and contamination by using industrial byproducts which belong to wastes. This is a new concept in which the polluting materials can be eliminated by wastes.

Based on the above-stated philosophy, the previous and possible utilization of PFA is classified into: 1) reclamation, embankment or backfill material, (2) light weight geo-material, (3) soil improvement, and (4) environmental material. Table 2.1 summarizes the outline for the status of pulverized coal fly ashes for these purposes. Among them, issues pertaining to the last item (4) have recently been started as joint research projects between Ibaraki University and Shimizu Corporation LTD. The reason why PFA, in particular, slurry PFA has been widely used is due to the fact that PFA has the following advantages:

i) low specific gravity leading to light weight,

ii) high pozzolanic activity enhancing strength, especially due to cement addition, and

iii) spherical shape of particles producing isotropy and then pumpability (see Fig. 2.3).

The most important issue in application of by-products for geotechnical practices is to prevent leachate of Polluting substances. One of possible techniques for achieving this is described in the next chapter.

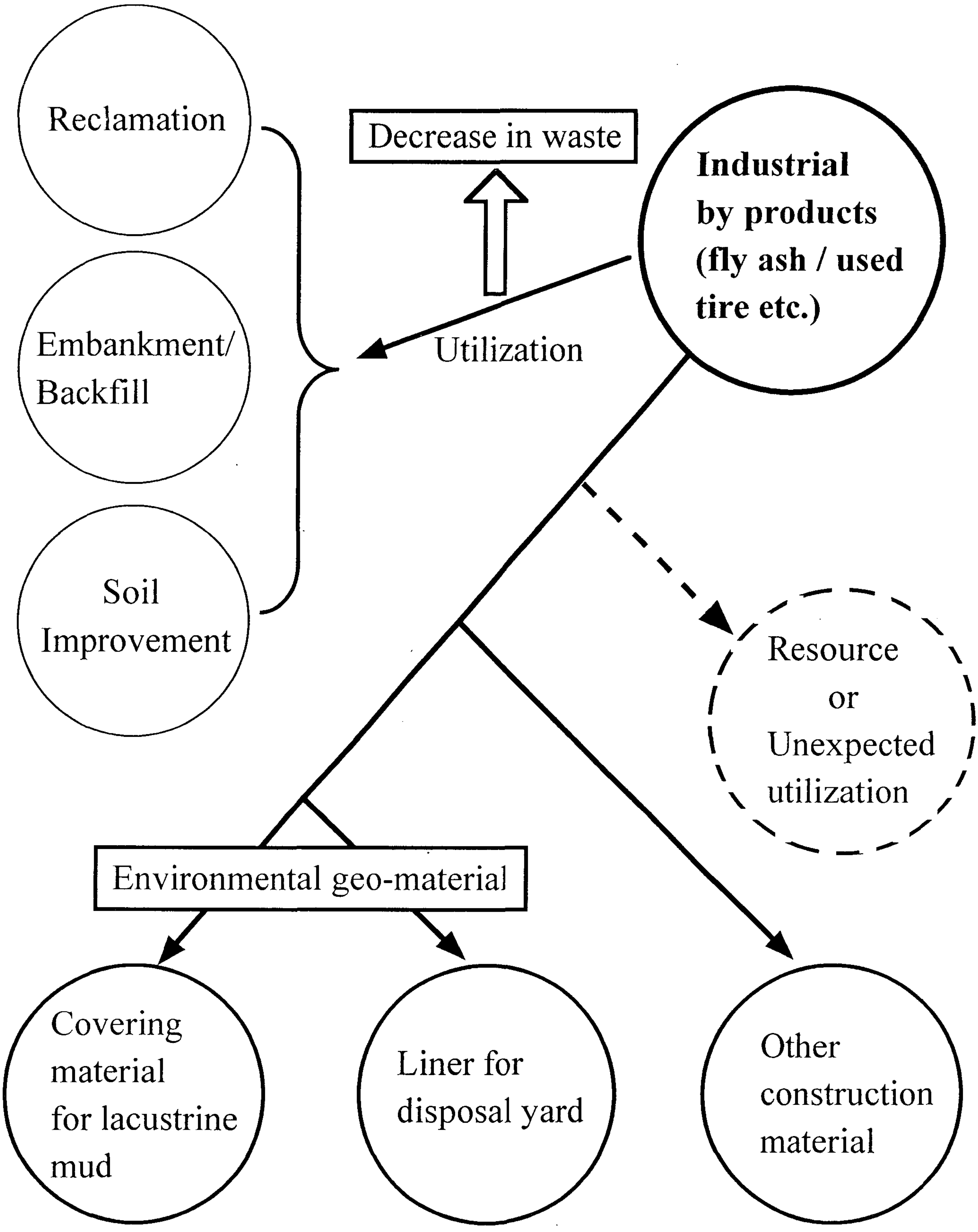


Fig 2.1 Philosophy for reducing geo-environmental impacts

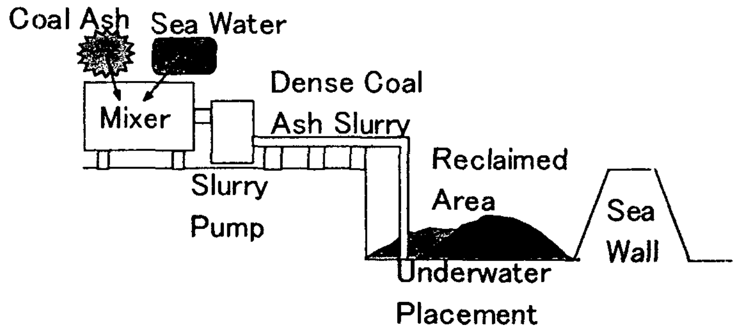
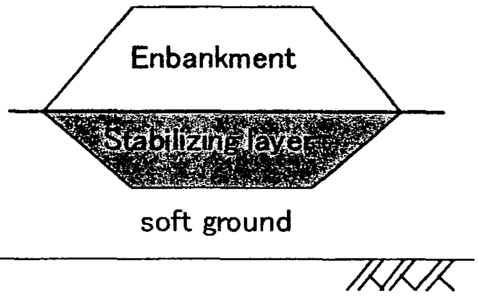
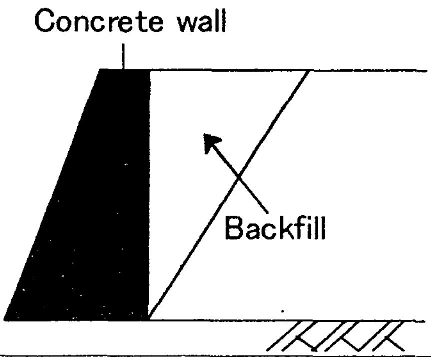
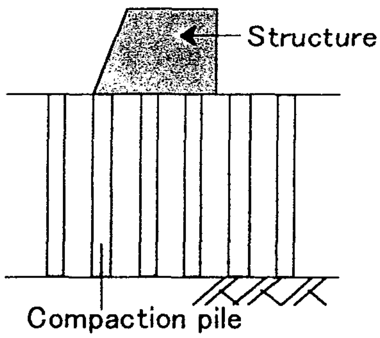
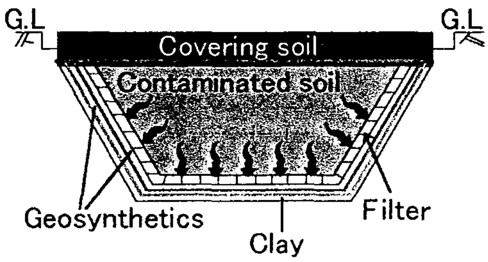
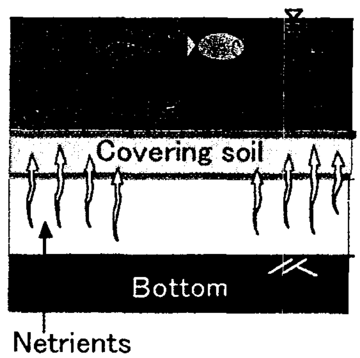
Usage	Field situation
Reclamation	
Embankment/ Stabilizing layer/ Backfill including light-weight Material	 
Soil improvement as draining or piling material	
Geo-environmental material (a) Conering soil at disposal facility (b) Filter	(a)  (b) 

Fig. 2.2 Example of utilization of PFA

Table 2.1 Status for utilization of PFA to geotechnical engineering practices

	Fundamental Aspects	Practical Aspects
Reclamation	Almost finished and being put into practice	Successful
Embankment/Backfill with cement and quicklime	Almost finished and being put into practice	Successful
Drain/Compaction	Almost finished and being put into practice	Partly, successful
Lightening geomaterial	Ongoing	Has been getting popular
Environmental geomaterial (I) such as liner/buffer for protection of leakage	Under research or under planning	Left for future possibility
Environmental geomaterial (II) such as filter for mitigation of contamination in soil	Under research or under planning	Left for future possibility

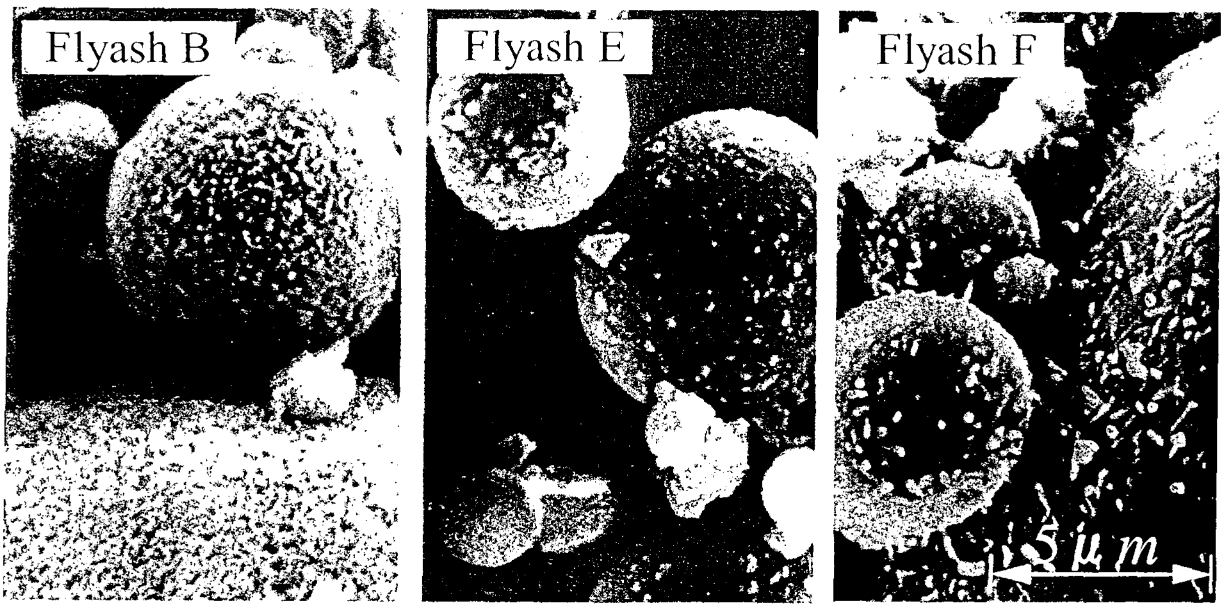


Fig. 2.3 Pictures of PFA particles by SEM

3. WASHING OF ASHES OF COAL AND REFUSE DERIVED FUEL

The amounts of coal fly-ash are increasing, and its beneficial reuse and efficient disposal method are significantly important problems in the industrial world. On the other hand, the electrical power plant of refuse derived fuel is attracting greater attention as a new technology for reducing the environmental impact. Therefore, a lot of exotic ash will exhaust from the new plant of refuse derived fuel, and the treatment of these ashes will also be new problems. Some ashes of coal and refuse derived fuel contain a very small quantity of chromium(VI), selenium, and boron, which must influence on human health. This problem has been an obstacle to the beneficial reuse and efficient disposal method of ashes.

To solve the above problem, Komine et al. (1999a) proposed the washing technology of ashes using hot-water. Fig. 3.1 shows the advantage of hot-water for washing. The proposed technology is to hot up the diffusion of heavy-metal ions and to eliminate these ions from the surface of ash-particle.

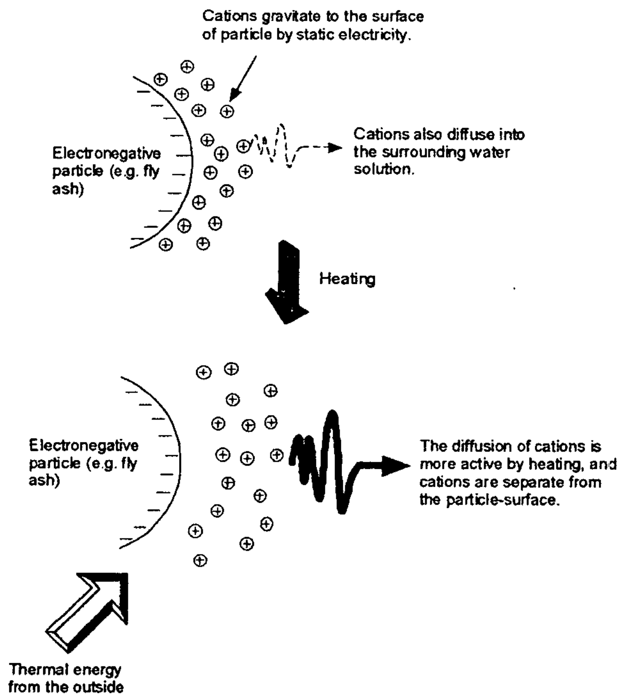


Fig. 3.1 Advantage of hot-water for washing.

Komine et al. (1999b) investigated the possibility of elimination of chromium(VI), selenium, and boron from coal by washing using hot-water in the laboratory. This study used four kinds of coal fly-ashes and RDF-ash produced from the power plants.

Fig. 3.2 shows the situation of washing-experiment in their study. They washed the ashes mentioned above by shaking of samples and hot distilled-water in 500 ml beaker. They also used hot artificial-seawater in their experiment. Seawater is expected to be available in actual plant for washing because seawater is very plentiful and cheap.

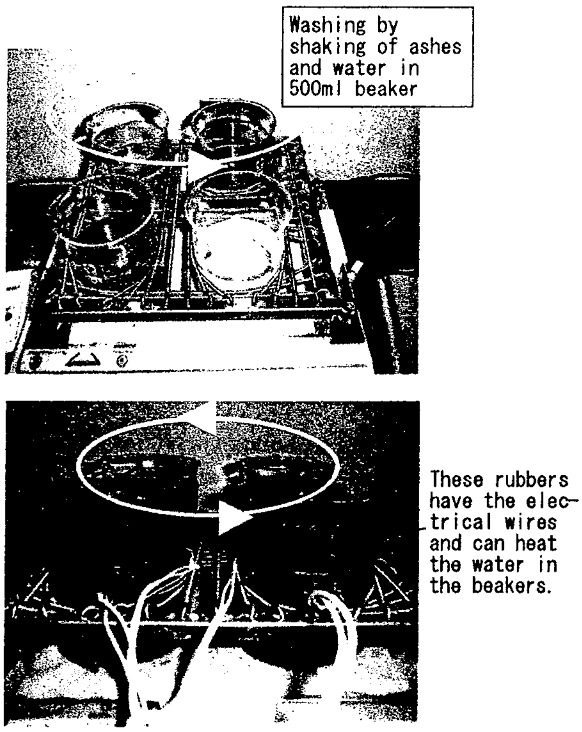


Fig. 3.2 Washing-experiment.

Figs. 3.3 and 3.4 example their experimental results. Fig. 3.3 shows the elimination of chromium(VI) from one kind of fly ash. Fig. 3.4 examples the elimination of boron from the same ash. As shown in Figs. 3.3 and 3.4, the repeat of washing is very effective for elimination of chromium(VI) and boron. These figures also indicate that the washing by hot distilled-water and hot artificial-seawater can eliminate chromium(VI) and boron effectively.

From all of their experimental results, it was found that it was possible to eliminate chromium(VI), selenium and boron from ashes of coal and refuse derived fuel by re-washing using hot distilled-water and hot artificial-seawater. Their study also succeeded in harmlessness of the one coal ash of which the concentration of chromium(VI) was ninefold of allowance of the Environmental Quality Standards for Soil Pollution by washing several times.

Furthermore, the boron and chromium can also be recovered from the washing solutions. Therefore, the ashes will be used as the resources of boron and chromium.

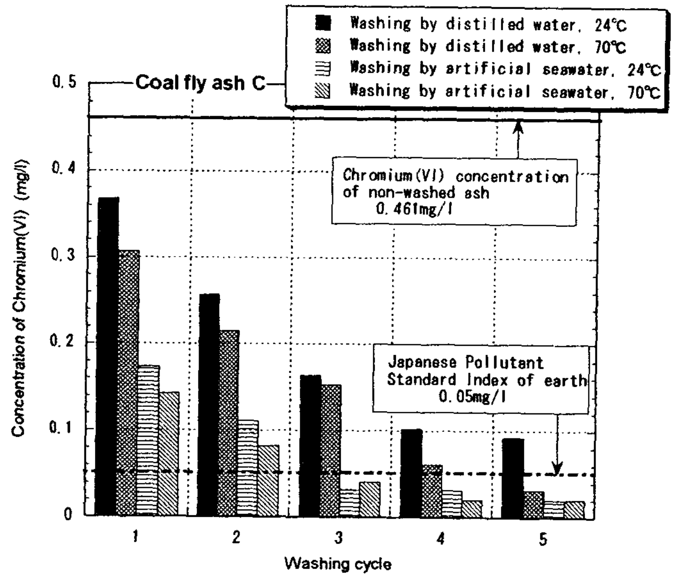


Figure 3.3 Experimental results of elimination of chromium (VI).

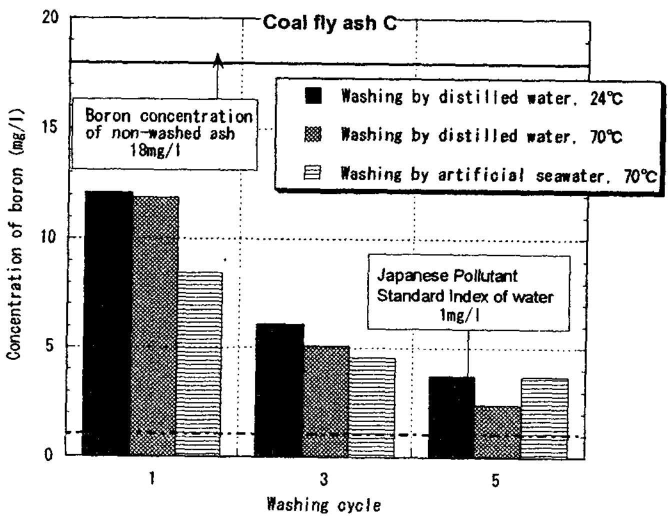


Figure 3.4 Experimental results of elimination of boron.

4 GEOTECHNICAL APPLICATION OF PFA -CASE 1: Reclamation and/or Backfill at Laboratory

4.1 Disposal Method of PFA-

Pulverized coal fly ashes (PFAs) have been disposed in the sea and on land in spite of being used in various fields in the cement industry, concrete additives and road materials. Utilization as fill materials for structural fill and backfill is expected because such projects require enormous quantity of PFA.

In Japan, sea disposal of PFA has increased because of the shortage of land disposal sites. The currently used disposal method of PFA for reclamation is classified into three types : dry, wet and slurry disposal systems.

The low density of PFA given by the wet disposal results from the free sedimentation of particle aggregates (Yasuhara et al., 1988). Such free sedimentation, however, can be avoided through the underwater placement techniques which give PFA a higher density (Horiuchi et al., 1985). This material has been named high density ash slurry (HAS) by Horiuchi et al. (1985), detail of whose placement method is shown in Fig. 2.2 and Fig. 4.1. Horiuchi et al. (1985) indicated that reclaimed ground by HAS provided great potential for producing stable reclaimed land.

Following the work by Horiuchi et al. (1985), the present chapter aims at demonstrating the advantages of the HAS reclamation method from the viewpoint of the improvement of strength and bearing capacity and hence the stability of reclaimed landfill. This coal fly ash slurry appears to be a good component for the slurry, due to the following properties; (1) Lower specific gravity, (2) Higher pozzolanic activity, and (3) Spherical shape of particles. Property (1) provides the advantage of light weight. Property (2) is valuable for strength enhancement with cement addition [20, 2, 3]. Besides these, property (3) contributes to good pumpability. In some projects, fly ash/cement slurries have

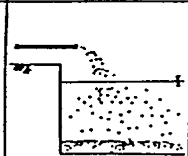
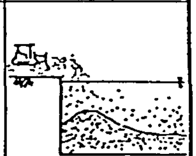
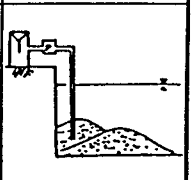
	System Process	Appearance
Wet Disposal System	① Mixing Fly Ash with a large amount of sea water. ② Pumping the low density FA slurry to the ash pond. ③ Spreading the FA slurry into the ash pond.	
Dry Disposal System	① Mixing with sea water at around the optimum water content of Fly Ash. ② Transfering the humidified FA to the disposal site by belt-conveyor or dump trucks. ③ Spread the humidified FA into the ash pond.	
Slurry Disposal System	① Mixing with sea water by the double mixing method to make the high density Fly Ash slurry. ② Pumping the high density slurry to the disposal site ③ Placing the high density slurry onto the bottom of the ash pond.	

Fig.4.1 Disposal methods for coal fly ash

actually been used for grouting ((littlejon, 1978). However, fundamental information, including relationship between strength development and composition of the slurry, its triaxial strength and applicability for underwater placement, has not yet been reported on.

4.2 Bearing Capacity of Reclaimed PFA

To investigate the bearing capacity of PFA, both plate loading tests and cone penetration tests were carried out using a laboratory model in a poly-acryl soil tank (1.0m length, 0.8m width, and 0.5m depth) as shown in Fig. 4.2. Two kinds of PFA with a calcium oxide (CAO) content of 4.5% (labeled A) and 2.0% (labeled B), respectively, were used for plate loading tests. Portland cement or gypsum was added as a cementing material in some tests. The details for all types of test are listed in Table 4.1.

Static cone penetration tests (CPT) and portable cone penetration tests (PCPT) were conducted to investigate the bearing capacity of three models : dry disposal PFA with 1% and 0% cement added, called DAS, and slurry PFA (HAS). The rates of penetration are 2 or 3 mm/sec and 1mm/sec, respectively, for the CPT and PCPT.

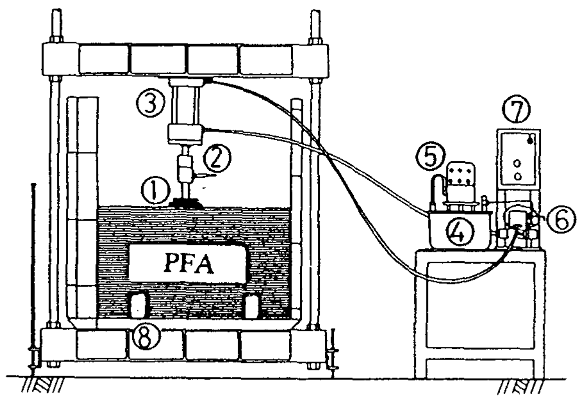


Fig.4.2 A layout of model footing testing equipment

Table 4.1 Test conditions and CaO content

Fly ash	No.	Reclamation method	Combination (%) FA:Cement:Gypsum	CaO (%)
A	A1	DAS	100: 0: 0	4.9
	A2	DAS	96: 2: 2	7.0
	A3	DAS	98: 2: 0	6.7
B	B1	DAS	100: 0: 0	2.0
	B2	DAS	99: 1: 0	2.6
	B3	HAS	100: 0: 0	2.0

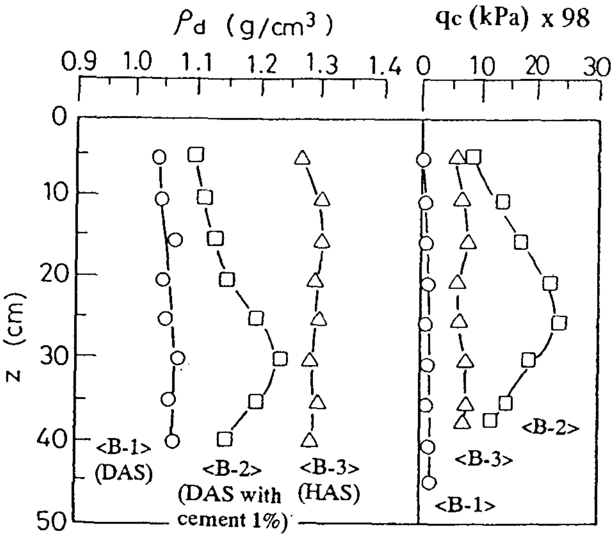


Fig.4.3 Distribution of ρ_d and q_c against depth (Series B tests)

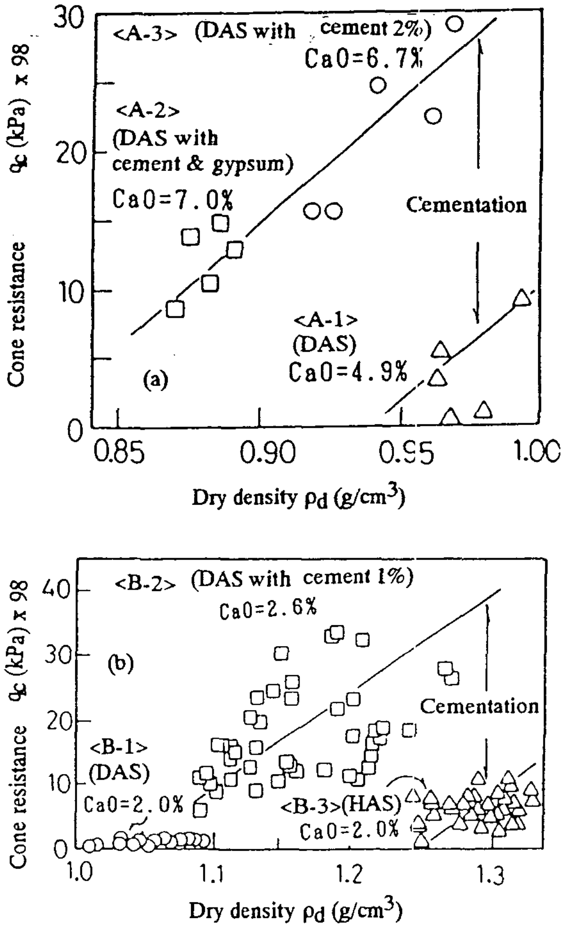


Fig. 4.4 Relations between q_c and ρ_d
((a)fly ash-A, (b)fly ash -B)

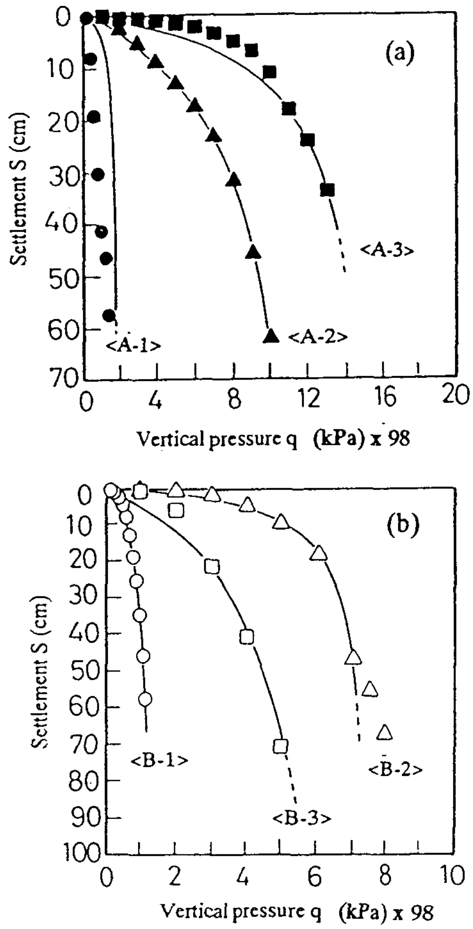


Fig.4.5 Hyperboric approximation for load versus
settlement curves ((a)fly ash-B, (b)fly ash - B)

4.3 Resistance and bearing capacity characteristics of PFA model ground

(1) Bearing capacity from CPT : the variation of the cone resistance, qc, obtained from CPT on PFA-B are plotted against depth in the model, in Fig. 4.3. Fig. 4.4 plots the variations in CP resistance against the dry density for two kinds of PFA. The results in Figs. 4.3 and 4.4 indicate the following:

i) The CPT resistance increases with the addition of cement. The increase in amount in CAO must contribute to the increased resistance force of PFA ground.

ii) The CP resistance of PFA relies primarily upon cementation and secondarily upon dry density.

iii) The high density is brought by slurry reclamation and the cementation is produced by cement addition.

Figs 4.5a and 4.5b illustrate the results from plate loading tests on the PFA model with two disposal methods. When the settlement versus vertical stress relation is assumed to be given by a hyperbolic function, the ultimate bearing capacity, q_f, is given as the ultimate value observed in each hyperbolic curve. The ultimate bearing capacity becomes larger in this order corresponding to the order of the magnitude of the CPT observed in Fig. 4.3.

4.4 Analysis of the results from plate loading tests

In analyzing the results from plate loading tests on soils, we should consider the compressibility of soils. However, the effect of compressibility is not considered in the conventionally used theory for bearing capacity because the soil is assumed as a rigid-plastic body. To eliminate this defect and to take into account the effect of compressibility in evaluating bearing capacity, Vesic (1972, 1975) extended the Terzaghi's classical theory into:

$$q_d = cN_c\xi_c\xi_{cc} + qN_q\xi_q\xi_{qc} + 0.5\gamma BN_\gamma\xi_r\xi_{rc} \qquad (4.1)$$

where ξ_{qc} ξ_{cc} and ξ_{rc} are coefficients relating the compressibility of soils given by:

$$\xi_{qc} = \exp\left[\left\{-4.4 + 0.6\frac{B}{L}\right\}\tan\phi' + \left\{\frac{(3.07\sin\phi')(\log 2I_r)}{1+\sin\phi'}\right\}\right] \qquad (4.2a)$$

$$\xi_{cc} = \xi_{qc} - \frac{1-\xi_{qc}}{N_q \tan\phi'} \qquad (4.2b)$$

$$\xi_{rc} = \xi_{qc} \qquad (\leq 1) \qquad (4.2c)$$

In Eq. (4.2a) I_r is rigidity index included in the cavity expansion theory by Vesic (1972) and is given by:

$$I_r = \frac{G}{c + p\tan\phi} \qquad (4.3a)$$

where G is shear modulus, c' is effective cohesion, and ϕ' is effective internal friction angle and p = $(1+K_o)\sigma_v/3$ (K_o is coefficient of earth pressure at rest : σ_v is effective overburden pressure).

$$I_{rr} = \frac{I_r}{1+\Delta_{av}} \qquad (4.3b)$$

where Δ_{av} is e a constant related to the compressibility

When we adopt Eq. (1) for evaluating the bearing capacity of PFA, we need the following parameters : (i) strength parameters in terms of the effective stress, c' and ϕ', (ii) shear modulus, (iii) a constant related to the compressibility, Δ_{av}, (iv) unit volume weight, γ'. Among the above, the shear modulus and the compressibility constant are given by the following relations:

$$G = \alpha_1 \left(\frac{p}{\sigma_0} \right)^{\beta_1} \qquad (4.4)$$

$$\Delta_{av} = c_0 (F_m - 1) \left(\frac{p}{\sigma_0} \right)^{m} \qquad (4.5)$$

where σ_o is unit effective stress (=98 kPa) and

$$F_m = \frac{3(1+\sin\phi')}{3+(3-4m)\sin\phi'} \qquad (4.6)$$

Table 4.2 Material parameters in analysis

	B1	B2	B3
ϕ' (°)	17.2	21.5	36.5
c ' (kPa) x 98	0.08	0.40	0.08
α_1	111.0	252.0	205.0
β_1	0.946	0.332	0.787
c_0	0.078	0.040	0.023
m	0.307	0.441	0.413
γ (g/cm^3)	1.50	1.66	1.74

Table 4.3 Predicted and experimental results of limited bearing capacity

Diameter of loading plate B(m)	Experimental results (kPa) x 98 B1	B2	B3	Calculated results (kPa) x 98 B1	B2	B3
0.15	1.47	7.76	7.02	1.4*	9.6	8.3
				3.8**	37.7	14.6
1.00	-	-	-	1.7	10.2	13.1
				3.9	28.1	17.2
5.00	-	-	-	3.2	12.9	35.6
				6.0	25.8	36.0
10.00	-	-	-	4.9	16.3	63.7
				8.6	28.2	57.3
20.00	-	-	-	8.5	23.0	119.9
				13.7	34.4	95.8

* : Limited bearing capacity calculated by Terzaghi's formula
** : Limited bearing capacity calculated by Vesić's formula

Experimental constants, α_1, β_1, c_c, and m included in these equations are determined from Fig. 4.4 and Fig. 4.5, using the results from oedometer and undrained triaxial tests, respectively. Each value used for the present analysis is summarized in Table 4.2.

Bearing capacities for three cases calculated using the Terzaghi's formula and the Vesic's Eq. (4.1) are summarized in Table 4.3 and compared with those observed in plate loading tests. Although the diameter of the loading area for tests in the laboratory was restricted to only one of 15cm, the calculated results include the variations of bearing capacity with the diameter. The upper values in Table 4.2 show the results calculated using the Terzaghi's equation which does not consider the soil compressibility, while lower value shows the results calculated using the Vesic's equation which takes it into consideration. In comparing both values, it is pointed out that in the case of the Vesic's value being larger than the Terzaghi's one, the PFA ground should be regarded as the non-compressible and can be evaluated using Terzaghi's conventional bearing capacity theory. The small value with the underline in both columns was adopted for prediction. Thus the calculated bearing capacity is plotted against the diameter of loading plate in Fig. 4.6. The following is also indicated from Table 4.3 and Fig. 4.6:

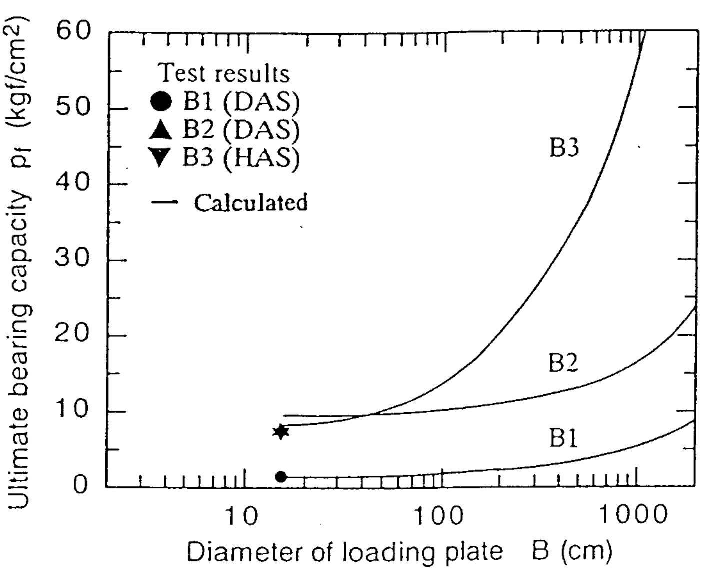


Fig.4.6 Relation between coefficient of Ki and G

i) the bearing capacity calculated using Terzaghi's equation agrees well with that observed in small scaled plate loading tests;

ii) it can be said that the calculated results for bearing capacity of PFA that not much of an increase in bearing capacity for B_1 and B_2 with increasing diameter of loading plate should be expected. On the other hand, the bearing capacity of HAS considerably increases with increases in the diameter of loaded area, B;

iii) when the diameter of loading plate is beyond 5.0m, the bearing capacity from Terzaghi's equation is lower than that from Vesic's equation by Eq. (4.1). This suggests that it is necessary to consider the compressibility when evaluating the bearing capacity in the case of larger diameters of loaded plate as may occur in the field.

5 GEOTECHNICAL APPLICATION OF PFA -CASE 1: Reclamation and/or Backfill at Field-

Man-made islands of 100m in diameter are often made in the construction of bridges. In conventional methods, such man-made islands are constructed by filling sandy soils into a steel pile cofferdamed area. However the following problems have frequently been encountered;

(1) Sliding failures of the seabed induced by the load of the fill.

(2) Insufficient strength of the fill for subsequent construction work.

(3) A large displacement of the cofferdam wall caused by lateral earth pressure exerted by the fill.

All these problems relate to the high density and low strength of the fill, therefore they can be avoided by improving the filling method. For example, problem (1) can be solved by using a lower density material. Problem (2) can be solved by providing a self-hardening property to the fill. Problem (3) is alleviated by decreasing fill density and/or filling a self-hardening material in layers, as shown in Fig. 5.1 where submerged density of $0.6t/m^3$ slurry and $0.8t/m^3$ sand are compared. For a solution to these problems, our experience points in the direction of underwater placement using a light and self-hardening material as the fill. However this new idea differs considerably from conventional filling methods and there is no precedent in actual construction projects.

The Hakucho Ohashi (The Muroran Bay Bridge), is being built in Hokkaido. The foundations of the two main towers are being built on 67m diameter man-made islands made on the soft seabed. For the construction of these man-made islands, a new filling method consisting of underwater placement of self-hardening light weight slurry into a coffer-dame area was applied instead of the conventional sandy soil filler. The authors carried out a series of studies to confirm the merits of underwater placement of PFA slurries (Horiuchi et al., 1992, Kawasaki et al., 1992, Yanagihara et al., 2000).

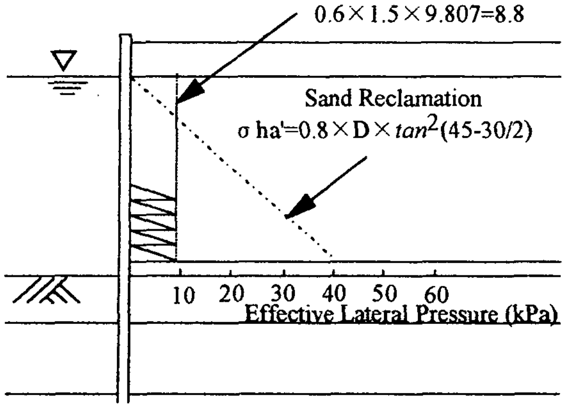


Fig. 5.1 Advantage of Slurry Placement on Lateral Earth Pressure

5.1 Specifications for Slurry Placement

The composition of the slurry was PFA, volcanic ash, ordinary portland cement and seawater.

Humidified PFAs were transported by truck in 2.5m^3 bags from the Tomato-Azuma power plant (Hokkaido electric power Co., Inc.) located 100km from the construction site. A finer volcanic ash, 0.29mm mean diameter, was used as a partial substitute for PFA and included as 30% of the volcanic ash content. Ordinary portland cement was used for strength enhancement of the slurry. The sea water in the cofferdamed pond was used as the mixing water. Quality specifications of the slurry were ; (1) slump : 11 cm (8～13cm), (2) bleeding rate : 0～3%. The strength requirement of the fill after 90 days is 100kPa in cohesion (c_u), which corresponds to 260kPa in unconfined compressive strength according to results of a series of triaxial tests. Since it seemed that there were many factors which could negatively influence the strength, such as a large variation in PFA properties and the q_u/s_u ratio of the slurry or decrease of density due to mixing with the seawater during the placement. A slurry composition was determined so as to develop cohesion of 320kPa, which corresponds to 840kPa in unconfined compressive strength in the laboratory test. Because the properties of the slurry differed greatly with the type of PFA used, the optimal composition for each type of PFA was determined as listed in Tab.5.1 through laboratory tests.

Table 5.1 Specs of Slurry

PFA	Cement content	Initial Water content	Mixing time (sec) Range	Average
MO	5 %	35 %	74～89	79
UL	5 %	40 %	66～112	84
PK	5 %	40 %	66～90	75
DA	5 %	35 %	73～93	78
GSEH	5 %	45 %	54～111	70
WA	4 %	40 %	62～144	71
LI	4 %	40 %	61～86	69
CV	4 %	50 %	66～159	83
CV/BA	5 %	35 %	64～85	73
CV/EB	5 %	60 %	70～143	91
CV/H/BA	4 %	55 %	76～82	78
Cv/BA/IP	4 %	55 %	67～126	74
UL/BA(1)	5 %	40 %	66～123	76
UL/BA(2)	5 %	50 %	66～80	70
WA/GSEH	5 %	45 %	70～86	74

Table 5.2 Slurry Quality

Properties	Specification	Slurry Prepared Mean value	Standard deviation
Slump (*cm*)	8～13	10.3	0.69
Wet density (*t/m*^{3})	1.60	1.60	0.073
28 day qu (*MPa*)	0.62	0.94	0.22
90 day qu (*MPa*)	0.84	-----	----
Bleeding ratio (%)	≦3	2.1	1.26

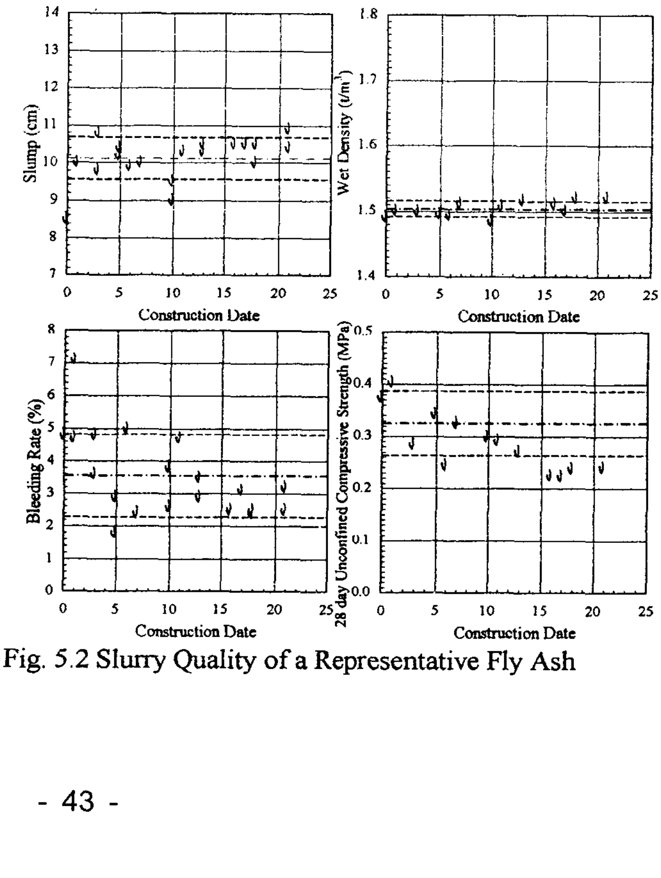


Fig. 5.2 Slurry Quality of a Representative Fly Ash

5.2 Results of Measurements

Properties of the slurry are shown in Table 5.2 and Fig. 5.2. There were large variations in slurry properties resulting from variations in the quality of the PFA used. Slurries using the same type of PFA have less variation in properties. The slurry quality can be controlled more precisely by limiting the type of PFA used. Throughout this filling work, no equipment failures nor pipe line blockages were experienced. Erosion of mechanical parts such as mixing blades or pipes was negligible, if anything.

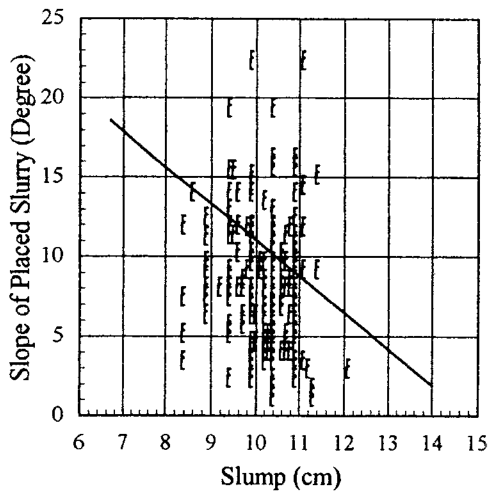


Fig.5.3 Slope measured during Placement

5.3 Slope and Temperature of Placed Mass

Shape and slope of the placed mass were measured daily during the filling work. The slope of each mass is plotted against the slump in Fig.5.3, in which the correlation line of $6m^3$ tests in Fig.5.4 is also shown. Though the correlation is not clear, the slopes are near to those recorded in placement tests using the $6m^3$ tank, as expected. The average slope of all the masses is 8.1 degrees, and most slurry appears to have been placed without failure of the slope.

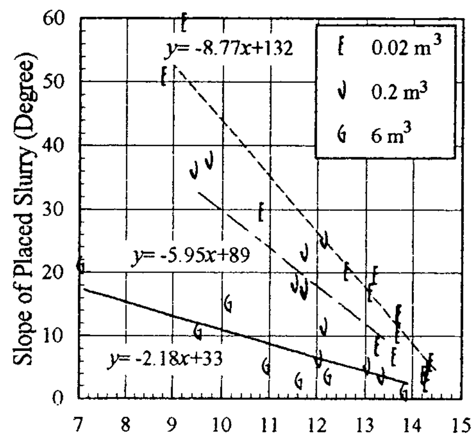


Fig.5.4 Slope and Slump at Lab Tests

Temperatures of the placed mass were measured at three depths, 6m inside from the cofferdam wall, using thermocouples. In Fig.5.5, the temperatures are plotted together with the depth of the fill, and both temperatures of the sea water and the atmosphere. Since slurry temperature was 10-20 ° C (mean

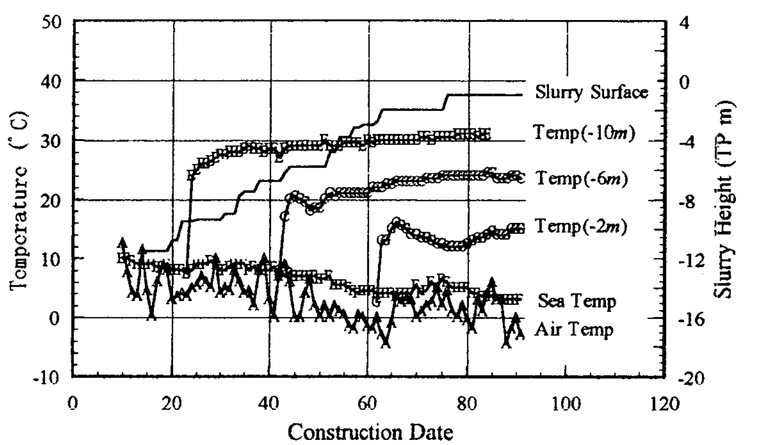


Fig.5.5 Depth and Temperature of Placed Slurry

value:14 ° C), caused by the high temperature of the humidified PFA, the sensors indicate a spontaneous increase in temperature just after contact with the slurry. The fill stayed at higher temperatures during the filling work, while the temperature of the seawater continued to decrease. This higher temperature results from heat supplied from the initial heat of the slurry and hydration of the cement in the slurry. Since most parts of the fill appear to stay above 10 ° C even in winter, inhibition of the strength development will be much less than that had been estimated.

5.4 Interaction of the Cofferdam and Placed Slurry

To confirm the advantages of reduced effective lateral earth pressures on the cofferdam wall, the lateral pressures were measured during slurry placement. A typical change of the effective lateral pressures is shown in Fig.5.6, in which the slurry surface depth change, determined using a ultrasonic density meter, is also plotted. The lateral pressure at -1.8m began to increase just after the slurry reached the pressure cell, and increased up to 4kPa at the end of the daily placement work. Since submerged density of the slurry used is 0.6 g/cm^3, the effective lateral pressure caused by the 0.94m thick is calculated as 5.64kPa. This pressure is close to but slightly higher than the actual one. This difference may be due to the existence of a lower density slime layer, which might accumulate at the edge of the mass during placement, and would increase the height measured. The effective lateral pressures at deeper points are also plotted in Fig.5.6. Since the slurry weight exerted pressure through the fill, the deeper the pressure cell was located the quicker the lateral pressure increased. The lateral pressure increase diminished over time, because of a small elastic displacement of the cofferdam wall induced by the water level difference between the inside and outside of the cofferdam or due to the lateral pressure of the placed slurry itself.

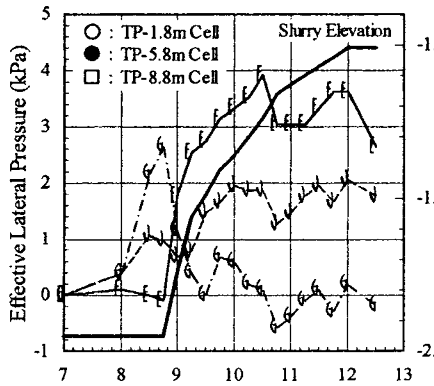


Fig.5.6 Effective Lateral Pressure Increase due to Slurry Placement

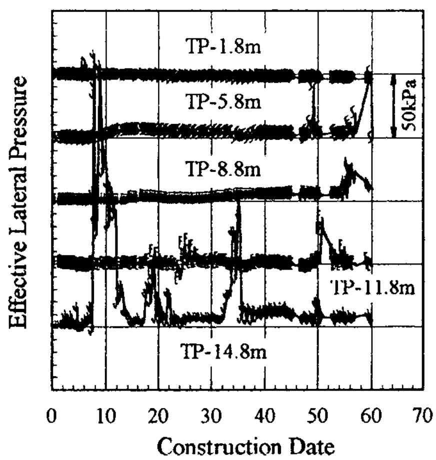


Fig.5.7 Effective Lateral Pressure throughout Filling Work

Fig.5.7 shows changes in the effective lateral

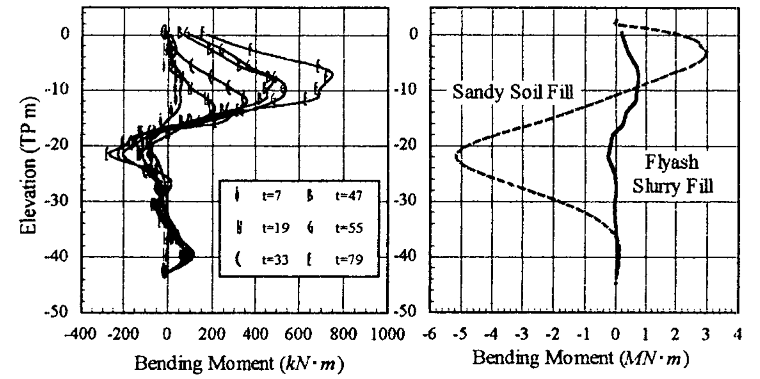


Fig.5.8 Bending Moment of Cofferdam Wall caused by Filling Works

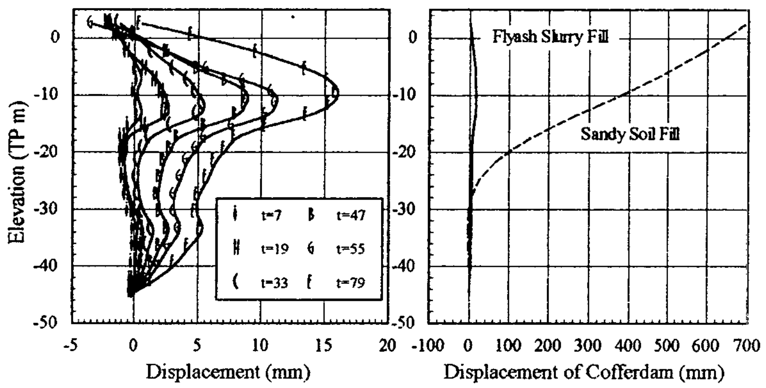


Fig.5.9 Displacement Profiles of Cofferdam Wall

pressures throughout the entire filling work. There were temporary increases, however they did not remain and had no cumulative effect. The average lateral pressure is 3-10kPa. The expected effective lateral earth pressure by the conventional method is 55KPa, therefore, it can be reduced to 1/18-1/6 by using the new filling method.

Bending moments of the cofferdam wall were calculated from the measured stresses. As shown in Fig.5.8, the moment increases with filling progress, however it did not exceed the designed maximum moment of 1.1 MN·m throughout the filling work. In Fig.5.8a bending moment profile calculated for a sandy soil fill, with 1.8 g/cm^3 wet density and 25 degrees internal friction angle, is also plotted to compare with the actual profile of the slurry filling. The maximum moment of the sandy soil fill is so large, that it would be necessary to increase the stiffness of the cofferdam wall to prevent its rupture. On the other hand, slurry filling shows a lower moment of less than 1/5. In this figure, depth of the maximum moment in the slurry filling method is located at a greater depth than that in the conventional method using sandy soil fill. This difference in depth results from the accumulation of the bending moment in the slurry method. Displacement profiles of the cofferdam wall measured with a inclinometer are shown in Fig.5.9. The displacement increased with filling progress, and reached a maximum value of 20mm at the end of the filling work. If we fill with a sandy soil, one calculation shows 700mm of displacement could be induced. Hence, the slurry filling method reduces displacement to 1/35 that of conventional method.

5.5 Properties of Fill

One month after completing the filling work, the properties of the fill ground were checked at several points by both laboratory tests using boring samples and in-situ tests. Distributions of unconfined compressive strength and wet density are plotted in Fig. 5.10, and each property varies considerably with location. The variations result from differences in the slurry used, curing periods and curing temperatures. In terms of the wet density, the boring samples exhibit a larger mean value and a smaller standard deviation than those obtained from the mold samples. This tendency results from the following:

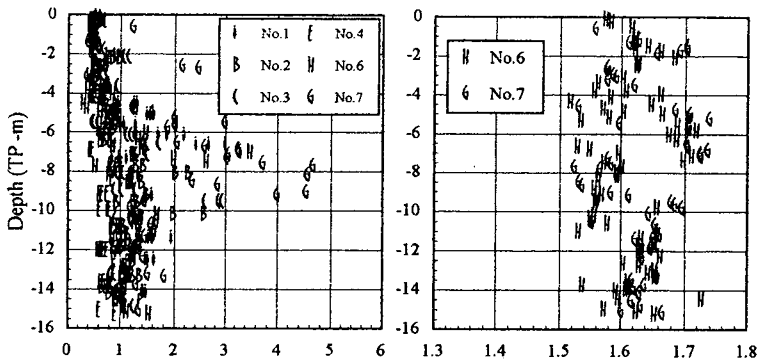


Fig.5.10 Distribution of Strength and Wet Density of Fill

Table 5.3 Properties of Fill

Properties	Specification	Boring samples	
		Mean value	Std deviation
Wet density (t/m^3)	1.6	1.62	0.058
Dry density (t/m^3)	------	1.14	0.087
Water content (%)	------	42.90	7.42
28 day qu (MPa)	------	1.06	0.61
90 day qu (MPa)	0.26	1.23	0.7
Elastic modulus (MPa)	------	359.7	256.3
Strain at Failure (%)	------	0.81	0.29

1) The degree of both consolidation and segregation of the placed slurries was greater than those in the molds.

2) During the placing of the slurries, scarcely any mixing with the sea water occurred.

As seen in Table 5.3, the fill's strength at 90 days is considerably greater than the specification, and is even greater than the slurry specification shown In Table 5.2. Comparing the strengths at 28days curing as shown in Fig.5.11, the boring sample shows a standard deviation three times as large, and a mean value 12% higher than the mold sample values. The large strength at TP-6～TP-10m in Fig. 5.10 due to PFA type used; i.e., PFAs used from TP-6 to TP-

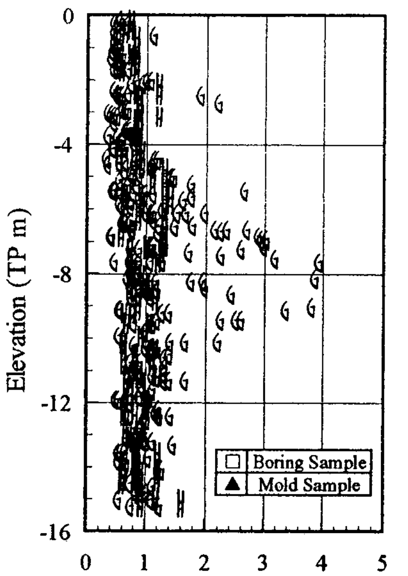


Fig.5.11 Strength Difference of Mold sample and Boring sample

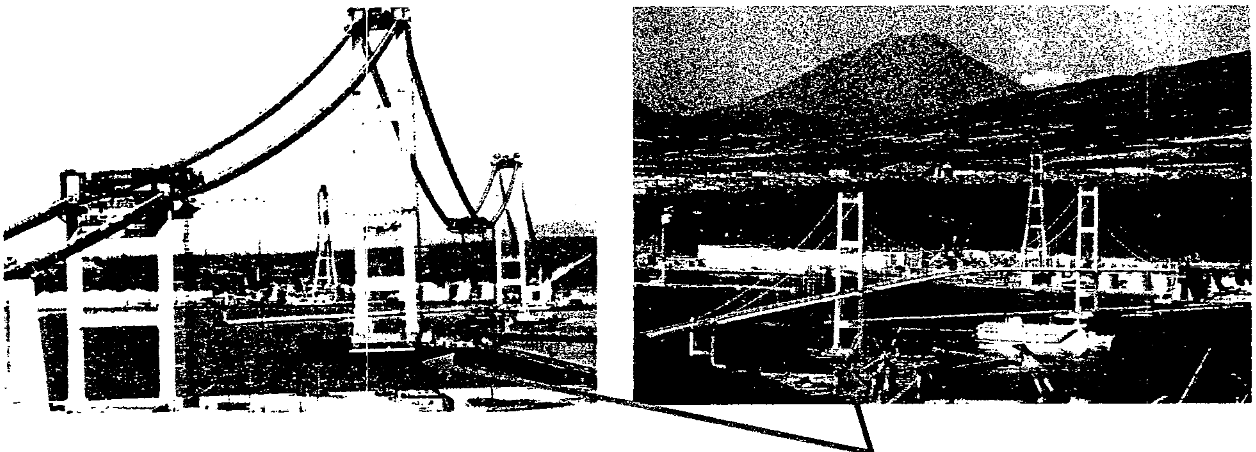


Fig.5.12 The Hakucho Ohashi Bridge and Man-made Island

10m placement showed a larger potential for strength development with time. If it is required to lower strength standard deviation, controlling the PFA type is important.

Seabed subsidence was measured during the filling. It reached 80mm at the end of the filling, however the subsiding rate is so gradual and small that it did not affect the subsequent construction work. Throughout the filling work, the following advantages of PFA slurry reclamation were confirmed:

1) Even though different varieties of PFA were used, the slurry could be prepared within the quality specifications by using appropriate equipment.

2) The new method reduces the lateral earth pressure to 1/18-1/6 that of the conventional sandy soil fill, and thus greatly reduces the bending moment and the displacement of the cofferdam wall.

3) In spite of filling work at low temperatures, the fill developed sufficient strength for subsequent construction work without requiring any soil improvement. In this filling work, 46.1 Gg of PFA was utilized. This new reclamation method can be used not only for island construction, but also for a variety of waterfront project works.

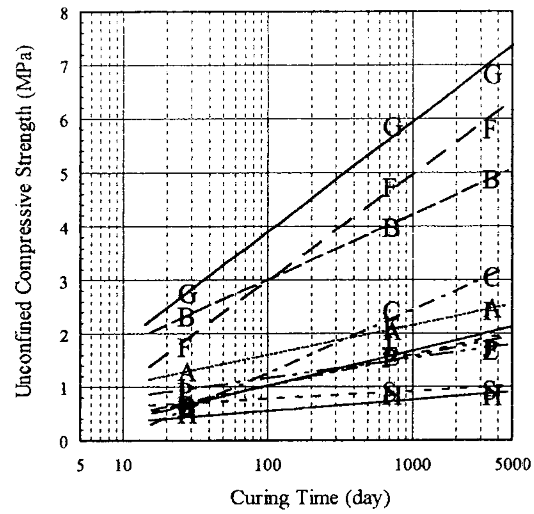


Fig.5.13 Long-term Strength of Slurry Fill

5.6 Long-term Stability of Fill

The Hakucho Ohashi project was accomplished at May 1998. Fig.5.12 shows the bridge together with the PFA fill. Long-term properties of the fill were checked using samples collected at 11 depths during excavation inside of the fill. The strength development is shown in Fig.5.13, where a long-term increasing of the strength is seen for all the samples more than 10 years after filling work. Among the samples, slurries using CV type PFA, which were used for placement at TP-6 to TP-10m, increase strength larger than the others.

Leaching tests were carried out using 10 year samples, and the results show a slight amount of chromium(VI) leaching, however, all the leachates are within the concentration of environmental quality standards for soil pollution in Japan.

For the reference, the procedure of the Hakucho Bridge construction using slurry PFA with volcanic ash soils is illustrated in Fig. 5.14.

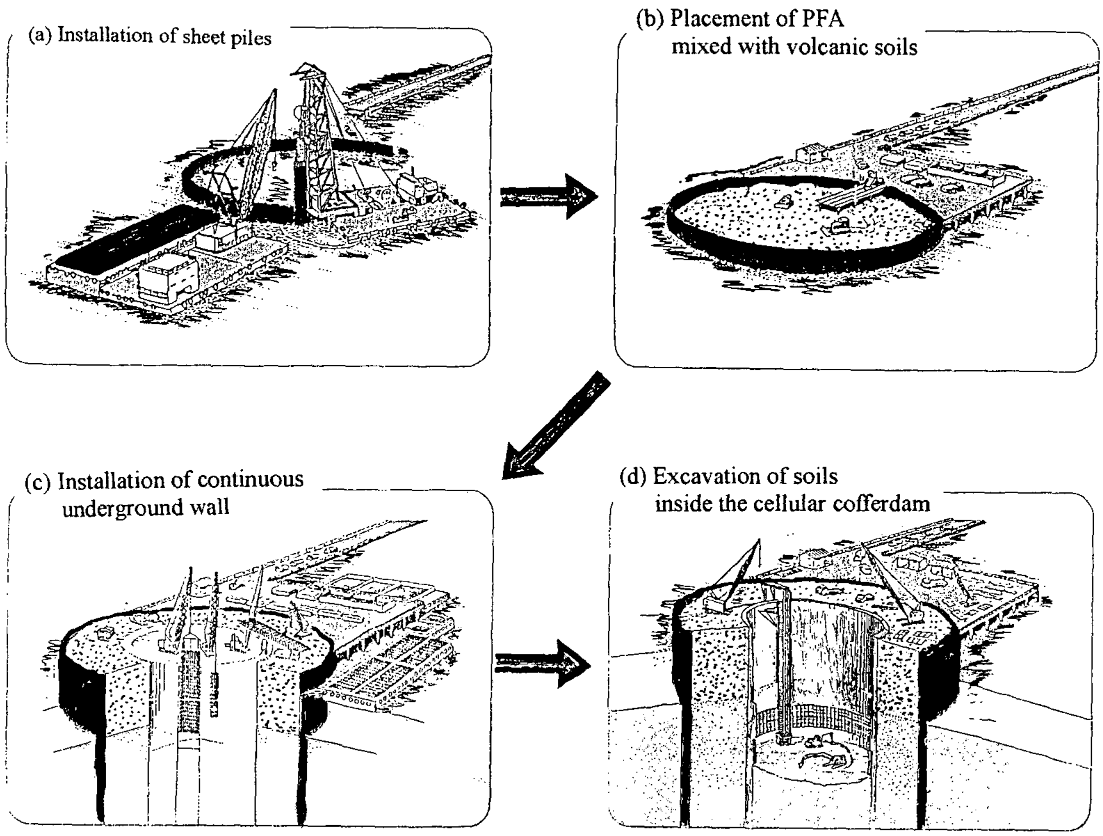


Fig. 5.14 Construction procedure of the bridge foundation

6 GEOTECHNICAL APPLICATION OF PFA-CASE 2: *Lightweight embankment/Backfill at laboratory-*

Unit weight of PFA is small on the average in comparison with that of ordinary soils excepting those such as volcanic ash soils and highly organic soils. A self-weight hardening effect is evolved with the elapsed time probably due to pozzolanic action and cementation (Horiuchi, et al., 1991 : Yasuhara and Horiuchi, 1996). These features are advantageous when it is used as a light-weight geomaterial, by adding a bubble creating agent (Yasuhara et al., 1998) or EPS beads (Pradhan et al., 1993). A number of samples were made for conducting unconfined and confined monotonic triaxial compression tests for a more precise understanding of strength and stiffness enhancement in mixed-type light-weight geomaterials. At the same time, an attempt was made to clarify the microscopic aspects of enhancement using the Scanning Electron Microscopy (SEM), Fluoroscopy (X-ray) and X-ray CT Scanner. The results obtained have been interpreted from a viewpoint of (i) the curing effect on enhanced stiffness and strength, and (ii) the chemical effect on improvement of mechanical properties.

6.1 Sample Preparation

All the specimens used for unconfined compression and triaxial compression tests (UU, CU and CD tests) as well as for microscopic investigation were prepared by mixing a foaming agent (a kind of animal protein) and cement with a fly ash whose constituents are summarized in Table 6.1. The mass per cubic metre of each of these materials is listed in Table 6.2. The procedure of preparing the admixture with three materials and water is illustrated in Fig. 6.1. The water content of specimens just after curing was 50 to 58% for underwater and 40% for open air on the average. The former increased up to 60 to 70% and the latter decreased markedly to 8% 150days later. The unit weight was aimed to be at least 1.0 kgf/m^3

Table 6.1 Cemical component of fly ashes used

Component	Percentage(%)
SiO_2	55.0
Al_2O_3	27.8
Fe_2O_3	3.5
CaO	5.0
MgO	1.5
P_2O_5	0.5
TiO_2	1.1
Na_2O	2.3
K_2O	1.0
SO_3	1.5

Table 6.2 Component of mixture for light-weight soil

Aimed Strength (kPa)	Cement (kg/m^3)	Fly ash (kg/m^3)	Water (kg/m^3)	Air foamed agent (kg/m^3)	Unit weight (tf/m^3)
490	80	550	349.2	0.9	1.0

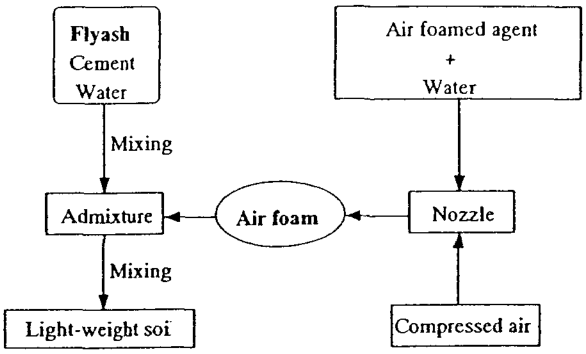
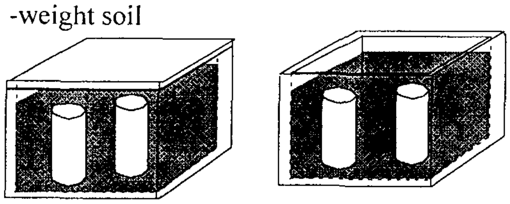


Fig.6.1 Sample preparation produre for light -weight soil



(a)with lid (b)Without lid

Fig.6.2 Underwater curing in the container

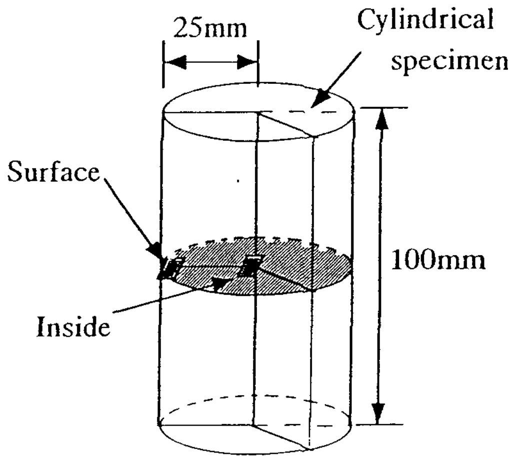


Fig.6.3 Locations of the samples pieces used for SEM and X-ray investigation

before curing in order to avoid floating under water. The specimens were cured in air in the basement of the department building and under water in a room with a constant temperature of 20°C. The underwater curing was either under artificial seawater and fresh water, with and without the lid at the top of the curing box as shown in Fig. 6.2. The curing periods in this case were 7 days through 330 days.

6.2 Testing Conditions

Unconfined compression and triaxial compression tests

The slurry mixture was poured into an aluminum split cylindrical mould (5cm diameter and 10cm height) made from aluminum lubricated with silicone grease. After a given period of curing, each specimen was set up for unconfined compression and triaxial compression tests. The triaxial testing equipment was in the form of the double cell to attain the more precise measurement of volume change since most of the specimens were not completely saturated, even after underwater curing. The confining pressures for three kinds of triaxial (UU, CU and CD) tests was 98 kPa and the consolidation period for CU and CD triaxal tests was 1hr. The axial strain rate was 0.1%/min both for unconfined compression and triaxial compression tests.

Microscopic investigation

A microscopic investigation for clarifying the interrelation with mechanical properties, with particular reference to the effect of curing was carried out using the Scanning Electron Microscopy (SEM), Fluoroscopy (X-ray) and X-ray Computerized Tomography Scanner (CTS). To specify what kind of compound might be formed in the specimen, pieces of sample 1cm square were carefully taken off from two locations near the surface and at the center and used for both SEM with 1200 magnifications and X-ray as shown in Fig. 6.3. The distribution of density across a section inside three specimens air and water cured for the same period of 330days was investigated using CTS.

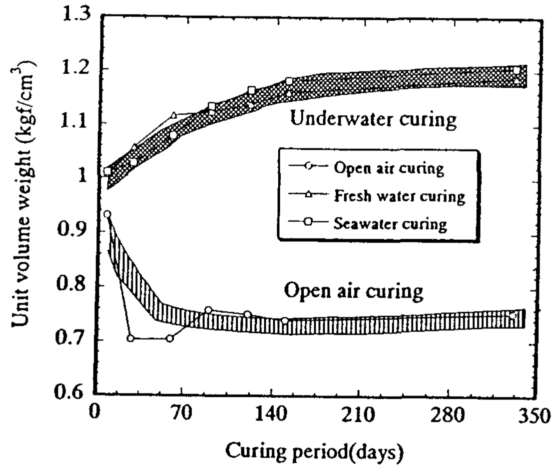


Fig.6.4 Variation of unit volume weight with curing period

6.3 Effect of Curing on Geotechnical Properties

The effects of curing (prolonged period, way of placement with or without the lid) on both index property and mechanical properties were investigated from a geotechnical engineering standpoint.

Effect on unit volume weight

The change in the unit weight of each specimen subjected to unconfined compression and triaxial compression tests was checked before and after curing. The results from this investigation are shown in Fig. 6.4. The shaded belt area indicates a trend of the variations with curing period. It is clear from Fig. 6.4 that unit weight of air cured specimens decreases at the beginning of the curing period and then becomes almost constant at below 1.0kgf/m^3. On the other hand, the unit weight of underwater cured specimens once increases and then largely remains constant with exceeding a little over 1.0kgf/m^3. These trends show the different influence of curing methods on the density of specimens. This may be related to enhancement of strength and stiffness.

Effect on strength and stiffness

No difference in shear behaviour was observed in three types (UU, CU and CD) of triaxial compression tests, therefore the results from CU tests presented in this paper are considered to be representative.

Figs. 6.5a and 6.5b show a set of deviatoric stress versus axial strain curves of three specimens with different periods of curing, 7days and 230days, respectively. A marked influence of the curing period on the stress versus strain curves can be seen from a comparison of Fig. 6.5a and Fig.

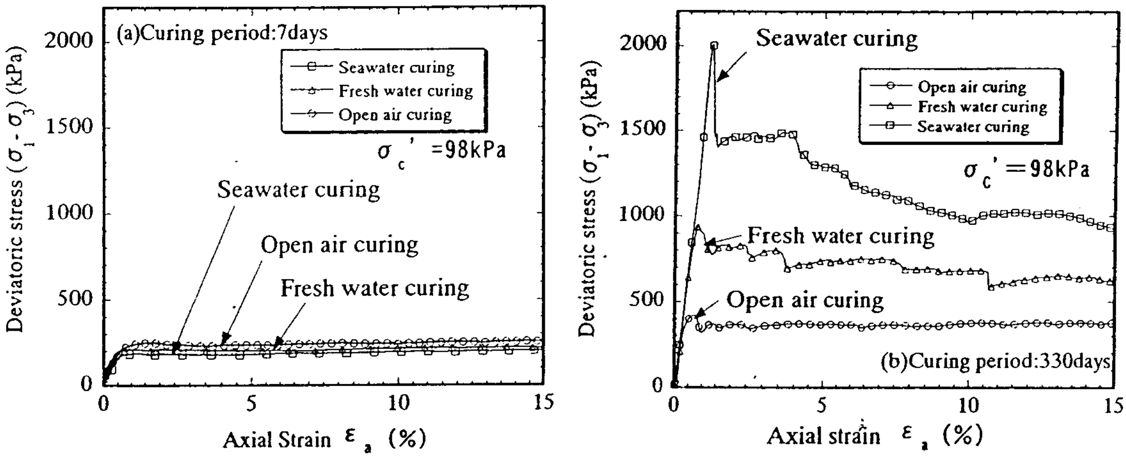


Fig.6.5 ε_a versus $(\sigma_1\text{-}\sigma_3)$ curves in CU triaxial tests

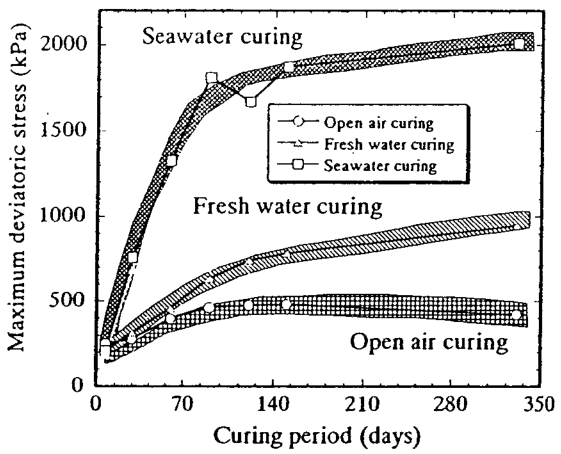


Fig.6.6 Variations of the maximum deviatoric stress with the curing period

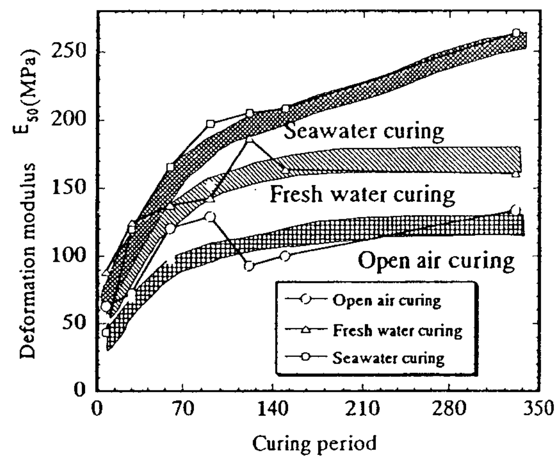


Fig.6.7 Variations of deformation modulus E_{50} with the curing period

6.5b. For example, the stress-strain curve becomes sharper and thus the difference in peak and residual strength becomes more marked with increasing curing period. The maximum deviatoric stress $(\sigma_1\text{-}\sigma_3)_{max}$ and the Young's modulus, E_{50}, were determined from stress- strain curves for all CU tests on specimens under different curing methods with different curing periods. The results on this investigation are plotted in Fig. 6.6 and Fig. 6.7, respectively, in the form of the variations of $(\sigma_1\text{-}\sigma_3)_{max}$ and E_{50} with the period of curing. The following is indicated from Fig. 6.6 and Fig. 6.7:

1) Strength and stiffness of specimens cured under water increases with the prolongation of the period of curing. This tendency is more marked in specimens cured under seawater than in those under fresh water.

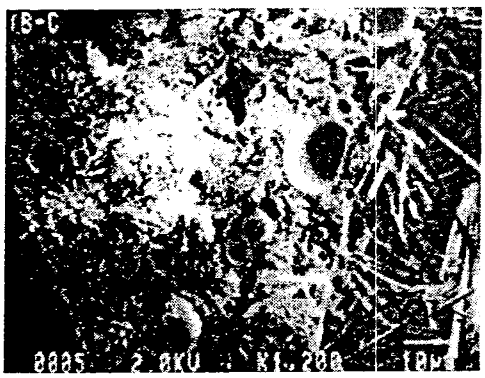
2) On the other hand, strength and stiffness are not so markedly enhanced in specimens cured under open air. Rather, $(\sigma_1\text{-}\sigma_3)_{max}$ decreases after a certain period of curing, although it increases at the beginning. Those tendencies may be in correspondence with those of unit weight in Fig. 6.4.

6.4 Effects of Curing on Microscopic Changes

Scanning Electron Microscopy (SEM)

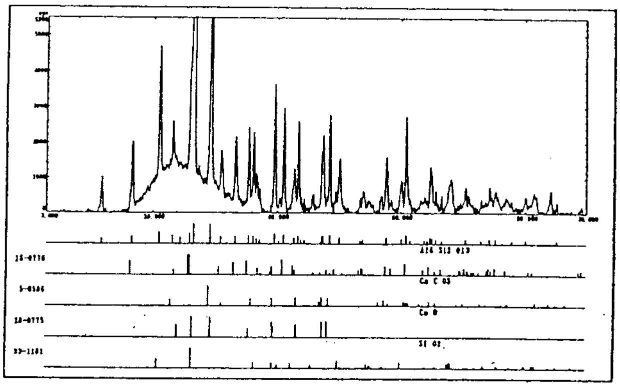
(a) Open air curing

(b) Fresh water curing (with lid)

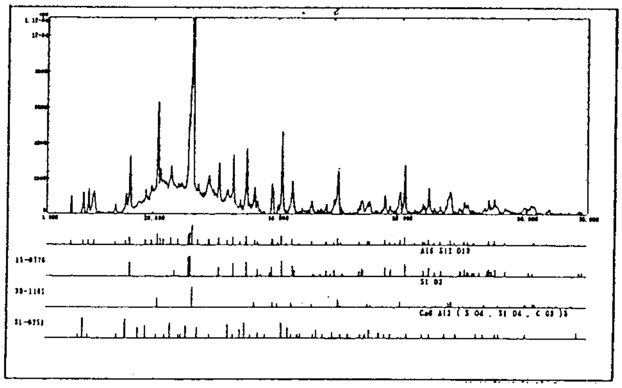


(c) Seawater curing (with lid)

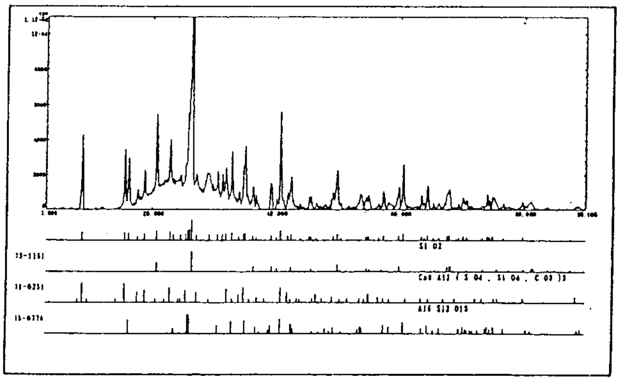
Fig.6.8 Pictures of the samples by SEM with 1200 magnification



(a) Open air curing



(b) Fresh water curing (with lid)



(c) Seawater curing (with lid)

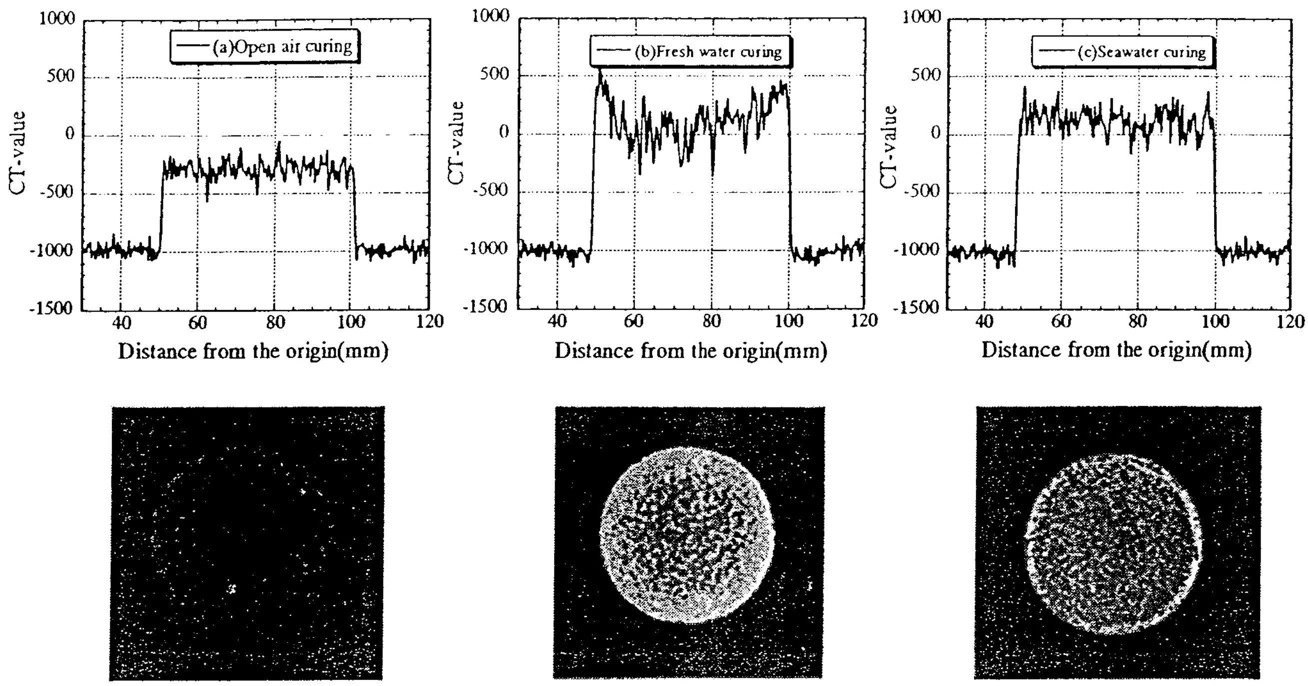
Fig.6.9 Identification of the crystal mineral samples by X-ray analysis

Fig. 6.8 demonstrates the results from SEM with 1200 magnifications on three pieces taken from the center of specimens as illustrated in Fig. 6.3. It is noted in Figs. 6.8a,b and c that in each specimen needle-like crystalline minerals have been formed in between the round fly ash particles with air bubbles. In particular, it should be emphasized that a number of these crystalline minerals has appeared in specimens cured under seawater in a closed container as shown in Fig. 6.1. These crystalline minerals were also recognized in pieces taken from the nearby surface of specimens. In the pieces from specimens cured under open air, however this type of crystal mineral was not observed. Judging from the difference between Figs. 6.8a,b and c, it is thought that the strength and stiffness enhancement described previously in 6.2 should have a close connection with formation of the needle-like crystalline minerals.

Fluoroscopic investigation (X-ray)

A X-ray analysis was conducted to identify the needle-like crystal mineral observed in SEM pictures and observed in pictures of pieces by SEM, and what kind of a role this unknown mineral plays in the behaviour of fly ashes based light-weight soils. Figs. 6.9a to 6.9c show a family of X-ray pictures for the pieces taken from the same locations of specimens as those used for SEM. Judging from the peak values observed in the results from X-ray analysis on specimens cured under seawater and fresh water, the existence of the reactive mineral etringitte, part of a compound mineral was surmised. Although, no reactive mineral was observed in the X-ray analysis in Fig. 6.9a, the needle-like crystal mineral observed in SEM is identified as etringitte from the X-ray analysis shown in Fig. 6.9b and Fig. 6.9c. It can also be concluded from this fact that the etringitte plays a key role in enhancement of strength and stiffness of light-weight geomaterials using fly ashes.

Computerized Tomography Scanning (CTS)



(a) Open air curing (b) Fresh water curing (c) Seawater curing

Fig.6.10 The results of CTS investigation

The pictures of three specimens cured in air, fresh water and seawater for a prolonged period of 430days were taken using X-ray CTS owned by the Geotechnical Engineering Group, Department of Civil Engineering, Kumamoto University, Japan (Otani, et al., 1999 : Otani, et al., 2000). The main purpose of this investigation is to examine the existence of cracks inside the specimen and cross sectional images of density. Fig. 6.10a to Fig. 6.10c illustrates the distribution of density and CT-value through a specimen cross section. The CT-value for cross sectional images is defined by:

$$\text{CT-value} = (m_t - m_w)\kappa / m_w \qquad (6.1)$$

where m_t is coefficient of absorption at scanning point, m_w is coefficient of absorption for water and κ is material constant. It is noted that the coefficient of absorption for air is zero. Therefore, when κ is assumed to be 1000, the CT-value of air becomes zero. The CT-images are black colour for low CT-values and white for high values. Thus from comparisons in Fig. 6.10:

1) The density of the specimens cured under water is higher than those that were air cured.

2) The distribution of density through the cross section in the seawater cured specimen is better than other two specimens cured under fresh water and air. This must be caused by homogeneous infiltration of seawater through the specimen. This is correlated with tendencies in the variation of increase in unit weight and enhancement in mechanical properties with the curing period as described in the previous sections 6.3 and 6.4.

6.5 A Micoscopic Perspective of Enhancement in Strength and Stiffness

As is well known in the field of concrete engineering, a chemical compound, part of the etringitte, is produced when hardening cement paste reacts with $MgSO_4$ under seawater (Avram et al., 1981). A Fe-poor compound produced at the same time causes the specimen to swell, leading to the loose texture in the specimen. This may make it easier for water to infiltrate into the specimen. It also induces an increase in density as etringitte is formed among the bubbles. At the present stage of our study, it is presumed from a microscopic point of view that enhancement in strength and stiffness of the light-weight soil with air bubbles are due to the above two factors.

6.6 Field Application of light-weight soils using slurry PFA (1)

Lightweight air mortar, in which a large part of cement was substituted by PFA, was used for structural fill surrounding a high-rise building to prevent subsidence and sliding failure of the low strength alluvial layer (Shioya et al. 1992). Fig.6.5 shows lightweight fill before and after surface covering. From 1993, 1800 tons of PFA have been utilized for this lightweight slurry.

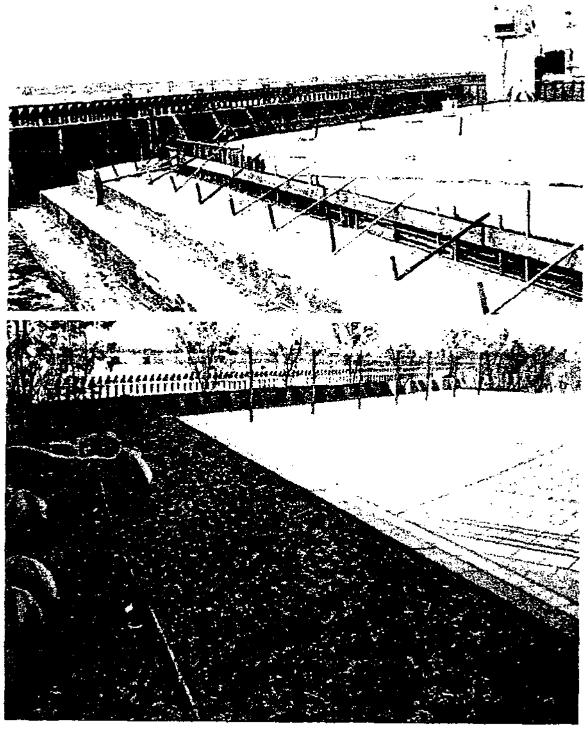


Fig.6.5 Lightweight slurry fill before and after surface covering

6.7 Field Application of light-weight soils using slurry PFA (2)

An air mortar, in which a large part of cement was substituted by PFA, was used for backfilling of pipe lines beneath power plant boiler. Fig.6.6 shows slurry placement around pipe lines, and slurry is filled in very narrow space.

In this project, 2400 tons of PFA were utilized.

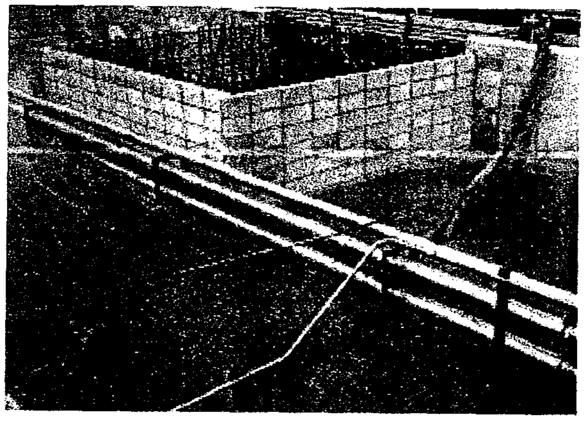


Fig.6.6 PFA air mortar backfill in power plant project

7 GEOTECHNICAL APPLICATION OF PFA -CASE 3: Soil Improvement-

New approaches of PFA usage have been challenged in many projects, i.e. special cements using PFAs combined with other chemicals were developed for soil stabilization and waste treatment. The following is the some examples pertaining to this category of usage, although the present paper does not aim at describing the status for this usage:

(1) Special cement composed of coal ash, cement and aluminum carbonate compound was effective for the stabilization of dredged soil (Kamon et al., 1987).

(2) Applicability of special mixtures provided by mixing lime with PFA for stabilization of dispersive soils was studied through a series of lab tests. The stabilized soils were concluded to be suitable for the earth-filled dam construction (Nontananandh et al., 1994).

(3) Mixture of fluidized-bed combustion coal fly ash and port-land cement showed high potentials for stabilization of municipal waste incineration PFA both on strength development and controlling leachates (Kamon et al., 1994).

(4) New synthesized cement using PFA and lime showed a high potential as a soil improvement cement developing lower strength (Sekiguchi et al., 1991).

(5) Potential of mixtures composed of PFA, shellfish incineration ash and FGD sludge was confirmed on soil stabilization. Appropriate mixtures were proposed through the lab tests (Takahashi et al., 1994).

8 GEOTECHNICAL APPLICATION-CASE 4 : Environmental Geomaterials-

The following is the possible and promising applications of PFA whose investigation are ongoing at Ibaraki University and Shimizu Corporation as the joint basic researches for developing the innovative environmental geomaterials:

i) Liner in waste disposal facility

ii) Backfill in radioactive waste disposal facility

iii) Filter or covering buffer for mitigation of contaminated soil

These have been now under fundamental researches at laboratory and field.

The new concepts should be developed in order to reduce environmental impacts to geotechnical practices using ideas such as: (1) life cycle assessment (LCA), and Inverse manufacturing (IM).

9 CONCLUSIONS

By focussing on the utilization of coal fly ashes as a typical case, the current paper aims at describing the previously successful experiences and future possibilities of geotechnical application of industrial byproducts for reducing environmental impacts. Through the previous experiences such as the stable foundation of the bridge and the lightweight structural fill, coal fly ashes are considered to be a very attractive and promising material from a geoenviromental point of view, because they own many advantageous characteristics. To promote usage of this kind, more efforts should be made on eliminating the polluted materials included in geomaterials and grounds as well as on protecting leachates of those materials in soils. Of course, as the primarily important issue, we should try to reduce the wastes from industries and individuals. Also, we should make as much effort as possible not to burn the wastes in order to reduce the green house effect due to increase in the carbon oxide, CO_2. By overcoming these difficulties, not only the innovative materials or resources but also the philosophy and concept will be proposed in the near future for promoting usage of industrial by-products more including coal fly ashes.

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