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MSW fly ash stabilized with coal ash for geotechnical application

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Abstract

The solidification and stabilization of municipal solid waste (MSW) fly ash for the purpose of minimizing the geo-environmental impact caused by toxic heavy metals as well as ensuring engineering safety (strength and soaking durability) are experimentally evaluated. The mixtures of MSW fly ash stabilized with cement and fluidized bed combustion coal fly ash (FCA) were used for unconfined compressive strength tests, leachate tests, and soaking tests. The behavior of soluble salts contained in the MSW fly ash significantly affects strength development, soaking durability, and the hardening reaction of the stabilized MSW fly ash mixtures. The cement stabilization of the MSW fly ash does not have enough effect on strength development and soaking durability. The addition of cement only contributes to the containment of heavy metals due to the high level of alkalinity. When using FCA as a stabilizing agent for MSW fly ash, the mixture exhibits high strength and durability. However, the Cd leachate cannot be prevented in the early stages of curing. Using a combination of cement and FCA as a MSW fly ash stabilizer can attain high strength, high soaking durability, and the containment of heavy metals. The stabilized MSW fly ash with cement and FCA can be practically applied to embankments.

Keywords: Municipal solid waste; Coal fly ash; Stabilization; Cement; Leachate

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1. Introduction

Municipal solid waste (MSW) is usually incinerated by the intermediate treatment facilities of local governments in Japan. Consequently, about 6000 Gg of bottom ash and fly ash are discharged from incinerators annually, and most of these ashes are disposed in landfill sites. Since incineration can give rise to harmful elements and toxic substances to be concentrated and compounded, respectively, most of the above elements remain in the MSW fly ash. Hence, the MSW fly ash must be carefully treated prior to its disposal in order to prevent environmental pollution. In the present system of incinerators in Japan, the MSW fly ash is mixed with the bottom ash, collected from incinerators and disposed of. Under the Waste Disposal and Public Cleaning Law revised in 1992, however, newly constructed incinerators are required to hold and separately collect the fly ash from the bottom ash. Thus, the fly ash must be treated by a method of melting, cement hardening, the addition of a chemical agent, or extraction prior to the disposal. In terms of the containment of harmful chemicals and volume reduction, the melting method is considered to be the most effective option available. Unfortunately, the method cannot achieve resource recovery due to its demand for high cost and energy [1,2]. Solidification by cement hardening has been regarded as another recommended method [3]. In the case of solidification, the government requires that the cement content be more than 150 kg/ 1 m^3 of MSW fly ash and the compressive strength be higher than 10 kg f/cm^2 (= 980 kPa).

In the past, research has been carried out on the material characterization and the geotechnical utilization of MSW bottom ash [4,5]. Recently, studies on the utilization of MSW fly ash as a construction material have been conducted in the US and Europe [6–8]. Research on the stabilization of MSW fly ash from a geotechnical viewpoint has also been conducted by Poran and Ahtchi-Ali [9], and they reported that the MSW fly ash in the US contains only a small amount of NaCl, can be effectively stabilized by lime, and is used as a road material. In Japan, however, due to the high composition of plastics in the MSW to be incinerated, MSW fly ash also usually contains a large amount of salt which affects the hardening reaction with cement or lime [10]. Thus, an effective method for MSW fly ash solidification is needed from technical, environmental, and economical points of view.

In this paper, the solidification and the stabilization of MSW fly ash for the purpose of minimizing the geo-environmental impact of toxic heavy metals leaching as well as ensuring engineering safety aspects (strength and soaking durability) are discussed. The stabilization method using cement and fluidized bed combustion coal fly ash (FCA) is proposed in terms of strength development, durability, and the control of heavy metal leachate.

2. Materials

2.1. MSW fly ash

The material used in this study is the MSW fly ash which was collected from the electrostatic precipitator of an MSW incineration facility under dry conditions. Particles

Table 1
Chemical composition of MSW fly ash

Cd (mg/kg)	225
Pb (mg/kg)	3750
Zn (mg/kg)	21,000
T–Cr (mg/kg)	235
As (mg/kg)	67
T–Hg (mg/kg)	4.5
Fe (mg/kg)	1650
Cu (mg/kg)	1800
PCB (mg/kg)	< 0.05
Ca (%)	9.5
S (%)	4.1
Cl (%)	13.0
N (%)	0.01

finer than 0.425 mm were used in the following experiments. In the incinerator, substances with low vapor pressure remained in the bottom ash throughout incineration, while those with high vapor pressure moved toward the exhaust gas and were consequently collected by the precipitator. Therefore, the properties of the bottom ash and the fly ash depended on the type of incinerator, temperature, and raw materials. The fly ash used in this study was collected from a fluidized combustion type incinerator whose temperature ranges from 800°C to 1000°C.

The chemical composition and leachate components of the MSW fly ash are shown in Tables 1 and 2, respectively. The leachate components of MSW fly ash were determined by a method as proposed in Section 3. The salt concentration and the electric conductivity of the samples were measured as per the sodium ionic selective electrode and alternating current methods, respectively. Of the electropositive elements, most of the silicon (Si) and aluminum (Al) remained in the bottom ash, while heavy metals such as cadmium (Cd), lead (Pb), arsenic (As), mercury (Hg), and potassium (K) were detected more in the fly ash than in the bottom ash due to its low vapor pressure. In view of the low boiling points of Cd and Hg such as 767°C and 357°C, respectively, they were

Table 2
Leachate components of MSW fly ash

Cd (ppm)	10.4
Pb (ppm)	19.6
Zn (ppm)	11.0
Cr(VI) (ppm)	0.03
As (mg/kg)	ND
pH	6.5
Salt concentration (%)	1.1
Electric conductivity (mS/cm)	12.7

Table 3
Physical properties of MSW fly ash

Particle density (g/cm^3)	3.03
Blaine specific surface area (cm^2/g)	107
Natural water content (%)	1.28
Liquid limit (%)	35.0
Plastic limit (%)	NP
Grain size distribution	
Sand fraction (> 0.075 mm) (%)	95.8
Silt fraction (0.005–0.075 mm) (%)	4.1
Clay fraction (< 0.005 mm) (%)	0.1
Uniformity coefficient	1.6
Coefficient of curvature	0.8

concentrated and contained in the fly ash. Due to high concentration leaching of Cd, Pb, and Zn from the used ash, it cannot satisfy the established environmental criteria of landfilling set by the Environmental Agency, Japan. Another important characteristic of the materials is the presence of high salt contents in the MSW fly ash such as NaCl and KCl, which has to be properly evaluated from an environmental point of view.

Table 3 exhibits the physical properties of the MSW fly ash. It mainly consists of sand-sized particles of uniformity coefficient of 1.6 which is too low to be compacted properly. The compaction curve of the fly ash is shown in Fig. 1. The mixing time with water has a significant effect on the consistency of fresh mixture, optimum water content and maximum dry density. A similar effect was reported on FCA by Kamon and Katsumi [11]. This may be due to the influence of soluble salts present in the MSW fly ash. In other words, the salts can dissolve when mixed with water and the mixture can consequently be compacted more densely. The compaction curve shown in Fig. 1 was obtained from the mixtures whose consistency has been changed due to the long mixing time.

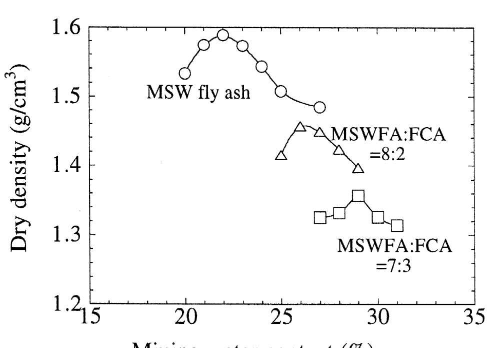

Fig. 1. Compaction curves of MSW fly ash.

3. FCA

FCA was used in experiments as an additive agent for the stabilization of MSW fly ash. The basic properties of FCA are shown in Table 4.

FCA is a by-product of the thermal power generation industry which uses coal fuel. The use of thermal power generators. which employ the fluidized bed combustion system, has recently become widespread as an independent means of electrical power generation in chemical industries and iron and steel manufacturing plants due to the many advantages this system provides. Such advantages include the efficiency of operating on the small scale necessary for independent power generation, the emission of less air pollution than such conventional methods as pulverized coal combustion system, and its ability to accept various qualities of raw coal for combustion. Even some electric supply companies have also constructed fluidized bed combustion systems for thermal power generation facilities. Consequently, the FCA generated as a by-product of fluidized bed combustion boilers has been increasing. Most of the FCA are presently being disposed of, but their utilization should be encouraged. One reason that the FCA is not being reused is that the characteristics of FCA differ significantly from those of the coal ash ordinarily utilized, such as pulverized coal fly ash. Due to the combustion system, FCA contains large amounts of unburned carbon, lime, and gypsum. However, the latter two components contribute to the hardening reaction in solidification process. Therefore, it has been proposed that a greater amount of FCA should be applied as road subgrade and subbase material and in soil stabilization [11–15].

4. Experimental procedure

Cylindrical specimens were prepared for unconfined compressive strength tests, soaking durability tests, X-ray diffraction (XRD) analysis, scanning electronic mi-

Table 4
Physical properties and chemical composition of FCA

Particle density (g/cm^3)	2.09
Blaine specific surface area (cm^2/g)	2850
Grain size distribution	
Sand fraction ($>$ 0.075 mm) (%)	7.6
Silt fraction (0.005–0.075 mm) (%)	80.0
Clay fraction ($<$ 0.005 mm) (%)	12.4
Ignition loss (%)	18.0
Chemical compositions (%)	
SiO_2	29.6
Al_2O_3	19.9
CaO	13.0
Fe_2O_3	3.2
SO_3	3.1
C	14.8

Table 5
Comparison of regulatory leaching tests in selected countries (after Kamon [21])

	TCLP Method 1311 EPA	DIN 38414 (DEV-S4)	AFNOR X31-210	JLT-46 Leaching test	NEN 7341 Availability test
Country	USA	Germany, Austria, Belgium	France	Japan	Netherlands
Test type	Batch	Batch	Batch	Batch	Batch
Particle size	< 9.5 mm	< 10 mm	< 4 mm	< 2 mm	< 0.125 mm
Leachant	HAc + NaOH pH = 2.88/4.93 (initial)	DW	DW	DW + HCl pH = 5.8–6.3 (initial)	DW + HNO_3 pH = 7/4 (fixed)
Sample amount	100 g	100 g	100 g	100 g	16 g
Maximum L/S	20 l/kg	10 l/kg	10 l/kg	10 l/kg	100 l/kg
Contact time per cycle	18 h	24 h	16 h	6 h	3 + 3 h
Agitation device	Rotation (30 rpm)	Rotation	Shaking table or rotation	Shaking table	Stirrer
Filtration	0.0006–0.0008 mm	0.00045 mm	0.00045 mm	0.00045 mm	0.00045 mm

croscopy (SEM) observations, and leachate tests. The specimens were prepared in accordance with the Practice for Making and Curing Compacted Stabilized Soil Specimens Using Rammer (Standard of the Japan Cement Association, CAJS L-01-1990, similar to ASTM D1632) for cases in which compaction was used, and in accordance with the Practice for Making and Curing Noncompacted Stabilized Soil Specimens (JGS T 821-1990) for cases in which compaction was not used. The specimens were sealed and cured under a constant room temperature of 20°C and a relative humidity of 80%. The mixing time and water content were determined based on the compaction characteristics aforementioned, in order to achieve changes in the consistencies of fresh mixtures.

Many researchers have pointed out that the procedure of leachate tests affects the test results [16–18]. In particular, the longer leaching time under agitation caused the encapsulation of heavy metals [19,20]. Although there are several regulatory methods available (see Table 5 [21], the leachate tests in this study were conducted with the following method whereby the agitation time was shorter (5 min). After unconfined compressive strength tests, the 30 g samples were crushed into clods smaller than 2 mm in diameter, and then mixed with 300 g of water. The filtrate was analyzed by an atomic absorption spectrophotometer after a 5-min period of leaching under agitation. Leachate tests established for landfilling by the Environmental Agency in Japan, which is listed as JLT-46 Leaching Test in Table 5, were also performed on some specimens.

5. Stabilization of MSW fly ash by cement hardening

Four types of stabilizers, namely, cement, cement-based stabilizers A and B, and FCA were assessed for the stabilization of MSW fly ash (Table 6). The reason for using stabilizers A and B is due to the significant contribution of $Al_2(SO_4)_3$ and $Ca(OH)_2$ on the stabilization of few waste materials [22]. The water content was set at 22%, fresh mixtures were mixed for 6 min, and the mixtures were poured into the molds without compaction.

5.1. Strength development

Fig. 2 shows the strength characteristics of the stabilized MSW fly ash. Each plot is the average of the duplicate values under the same experimental conditions. The FCA

Table 6
Mix proportions of stabilizers used

	Cement	$Al_2(SO_4)_3$	$Ca(OH)_2$	FCA
Cement	100	–	–	–
Stabilizer A	90	5	5	–
Stabilizer B	20	5	5	70
FCA	–	–	–	100

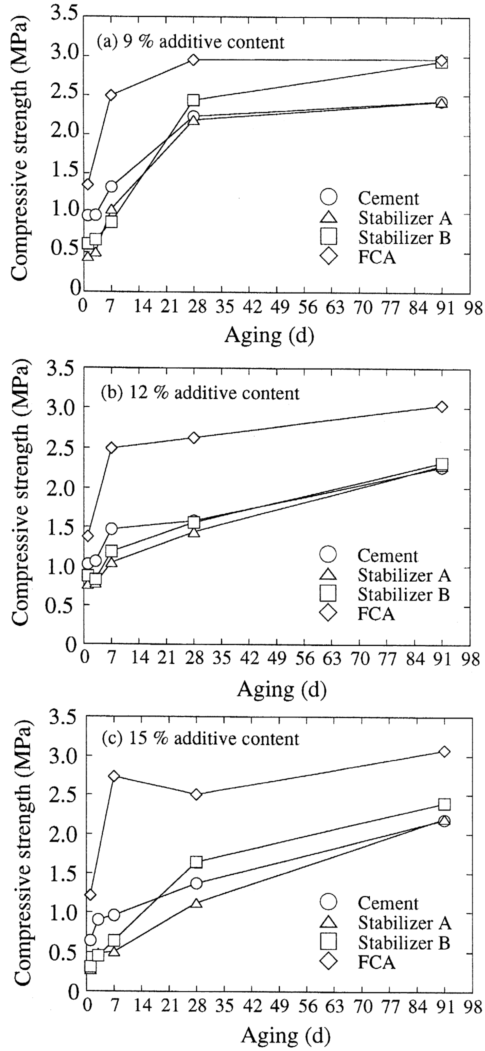

Fig. 2. Strengths of stabilized MSW fly ash.

differs remarkably from other stabilizers (cement and cement-based stabilizers) in its contribution to strength development. If stabilizers containing cement are used, the increase in strength will continue over a long period of curing (13 weeks), while the MSW fly ash stabilized by FCA can achieve a strength higher than 2 MPa in the early stages (1 week). The increase in strength after 7 days is not remarkable for any specimen. The MSW fly ash stabilized by FCA has achieved a higher strength than the fly ash stabilized by other stabilizers with respect to each additive content and curing period. The differences in additive content of the stabilizer relative to the MSW (9%, 12%, and 15%) do not induce any effect on the strength development.

According to the results of the XRD analysis (Fig. 3), no possible by-products formation has been noticed due to ordinary cement hydration except for a small amount of ettringite, while NaCl and KCl were markedly detected. In the SEM photos (Fig. 4), the crystals with parallelepiped or ring shapes were widely spread throughout the observed area. The needle-shaped crystals' presence has been observed only in the pore volumes between the crystals. An X-ray microanalyzer identified these parallelepiped, ring-shaped, and needle-shaped crystals as NaCl, KCl, and ettringite, respectively.

From these test results, the hardening mechanisms can be summarized as follows: soluble substances, NaCl and KCl, which do not dissolve during mixing, form a skeleton. Since cement and FCA adsorb the pore water due to hydration, the chemical deposition of the previously dissolved NaCl and KCl contributes to the formation of skeleton, but coats the cement and FCA to prevent the cement hydration. FCA is expected to contribute more to the chemical deposition caused by the water adsorption ability than cement or cement-based stabilizers. The above phenomenon further results in attaining a higher level of hardened strength.

5.2. Leachate characteristics of heavy metals

The leachate of heavy metals, such as Cd, Pb, and Zn, contained in the MSW fly ash should be addressed. The leachate characteristics, which were obtained through the abovementioned experimental method, are presented in Table 7.

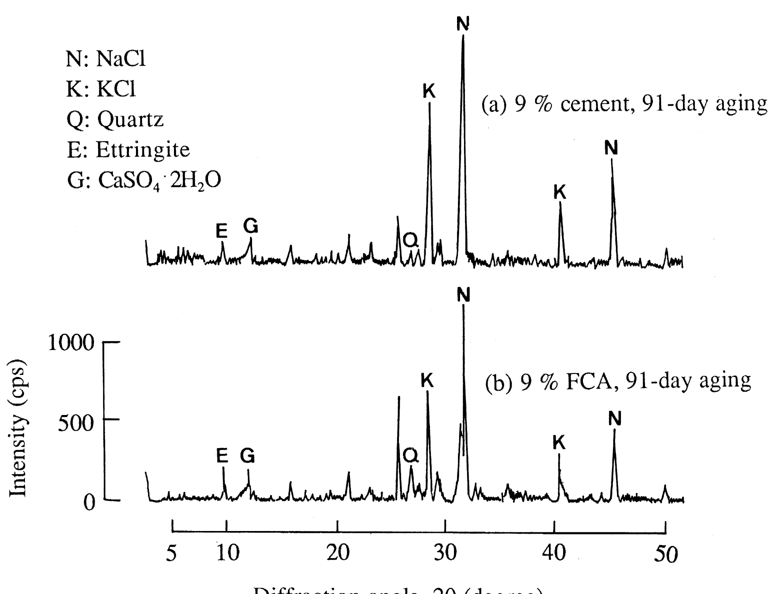

Fig. 3. The XRD patterns for stabilized MSW fly ash.

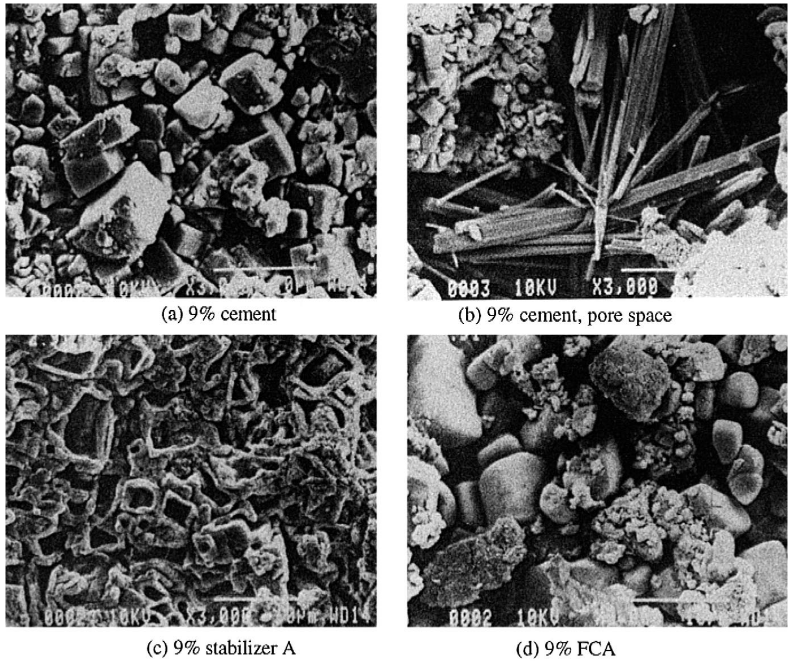

Fig. 4. The SEM micrographs of stabilized MSW fly ash at 91-day curing.

FCA differs from other stabilizing agents in its Cd leachate characteristics as well as in its strength development. Cd leachate from the specimens containing cement is lower

Table 7
Leachate components of stabilized MSW fly ash (9% additive content)

Type of stabilizer	Aging (days)	pH	Leachate concentration (ppm)			Salt concentration (%)	Electric conductivity (mS/cm)
			Cd	Pb	Zn		
Cement	7	9.0	0.14	0.14	ND	1.3	27
	28	9.1	0.08	0.19	ND	1.4	26
	91	9.7	0.06	0.28	ND	1.4	23
Stabilizer A	7	9.3	0.09	0.14	ND	1.4	27
	28	9.6	0.07	0.12	ND	1.4	25
	91	9.4	0.05	0.20	ND	1.5	27
Stabilizer B	7	9.3	0.11	0.14	ND	1.2	25
	28	9.6	0.09	0.14	ND	1.1	25
	91	9.6	0.07	0.18	ND	1.1	24
FCA	7	9.0	0.31	0.13	ND	1.4	25
	28	8.9	0.29	0.18	ND	1.3	22
	91	9.1	0.13	0.13	ND	1.0	23

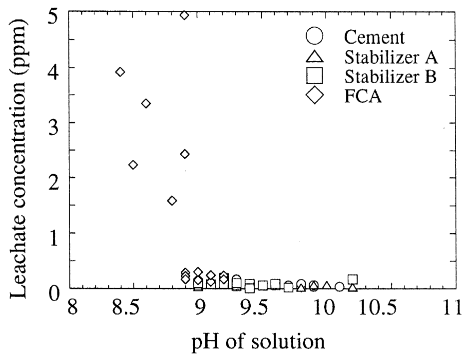

Fig. 5. Leachate concentration of Cd vs. pH of solution.

than 0.1 ppm in most cases in spite of the type of stabilizer or the curing period involved. High leachate concentrations of Cd were detected in the ash stabilized with FCA, especially in the early stages of curing, and the long curing period is required in order to satisfy the Cd leachate criteria (0.3 ppm) for harmful heavy metals, set down for landfilling by the Environmental Agency. The Cd leachate is closely related to the pH of the solutions (Fig. 5), which is consistent with the solubility chemistry of Cd. According to these results, if the leachate solution has a lower pH value than 9.0, the Cd leachate must be dealt with seriously. Since an alkaline environment is required for the containment of Cd, 1 week curing is needed when using FCA as the stabilizing agent.

The leachate of two other components, such as Pb and Zn, was not affected by the type or additive content of the stabilizers or curing period. Zn is considered to be stable as $Zn(OH)_2$, and hence, none is detected. The Pb leachate satisfies the leachate criteria established for landfilling by the Environmental Agency.

Table 8
Leachate components of stabilized MSW fly ash by soaking

Type of stabilizer	Aging (days)	pH	Salt concentration (%)	Electric conductivity (mS/cm)
Cement	7	9.1	1.1	2.5
	28	9.3	1.1	23
	91	9.3	1.1	21
Stabilizer A	7	9.4	1.2	24
	28	9.5	1.1	24
	91	9.6	1.1	23
Stabilizer B	7	9.1	1.2	25
	28	9.5	1.2	22
	91	9.0	1.1	21
FCA	7	9.0	1.1	23
	28	9.1	1.2	24
	91	9.4	1.0	23

5.3. Soaking durability

Since hardened mixtures of MSW fly ash consist of soluble substances such as NaCl and KCl, but not the cement hydrated by-products from the XRD analysis or the SEM observations, their durability under soaking conditions should be assessed from environmental and geotechnical viewpoints. Therefore, a series of soaking tests was performed, in which clods of the 30 g stabilized samples after a 7-day aging were soaked in 300 g of water.

The stabilized mixtures of MSW fly ash with cement or cement-based stabilizers gradually failed under soaking condition and broke into particles. However, the MSW fly ash stabilized with FCA was able to maintain its shape under soaking conditions, even though cracks and/or fractures were observed after 7 days of soaking. Table 8 shows the chemical properties of the water in which the samples were soaked. As the effects of the type of stabilizer cannot be confirmed by electric conductivity and/or the salt concentration of the soaked water, the mechanisms of soaking durability cannot be explained only in terms of salt leachate.

6. Effect of FCA on stabilizing MSW fly ash

It was previously stated that FCA affects only the strength development and the soaking durability but not the Cd containment. Both cement and cement-based stabilizers have an effect on the Cd containment, while cement hydration cannot be seen. Therefore, their multiple use can be considered. The effects of using both cement and FCA for stabilization purposes are discussed in this section. The mixing proportions are shown in Table 9, and the mixing water contents are determined by the compaction characteristics, as shown in Fig. 1.

6.1. Strength development

Due to compaction, the high strength development of the specimens has been observed, as shown in Fig. 6. The compressive strength depends on the FCA content;

Table 9
Mixing proportions for stabilization of MSW fly ash

Symbol	Mixing ratio			Mixing water content (%)
	MSW fly ash	FCA	Cement	
M-13	80	20	0	26
M-14	80	20	5	26
M-15	80	20	10	26
M-16	70	30	0	29
M-17	70	30	5	29
M-18	70	30	10	29

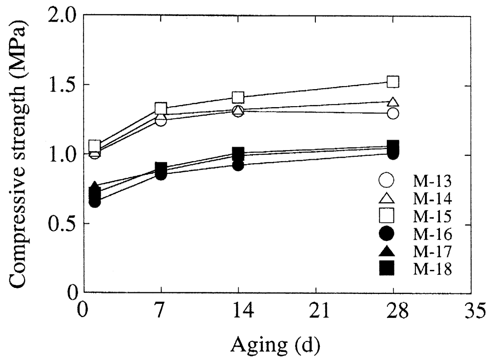

Fig. 6. Strength characteristics of stabilized MSW fly ash.

namely, lower contents of FCA caused higher strengths from the results previously presented in Fig. 2. As the aging time and cement content have little effect on the increase in strength, it is considered that the hydration of cement components does not

Table 10
Leachate components of stabilized MSW fly ash

Symbol	Aging (days)	pH	Leachate concentration (ppm)		
			Cd	Pb	Zn
M-13	1	8.3	4.49	0.38	0.17
	7	9.0	0.26	0.18	ND
	14	8.8	0.20	0.17	ND
	28	9.3	0.17	0.24	ND
M-14	1	9.9	0.08	0.15	ND
	7	9.5	0.08	0.18	ND
	14	9.8	0.08	0.26	ND
	28	9.7	0.05	0.25	ND
M-15	1	10.1	0.08	0.14	ND
	7	9.7	0.07	0.13	ND
	14	9.7	0.05	0.25	ND
	28	9.9	0.05	0.23	ND
M-16	1	9.3	3.05	0.29	0.11
	7	9.0	0.27	0.17	ND
	14	9.4	0.20	0.17	ND
	28	9.2	0.20	0.23	ND
M-17	1	10.1	0.06	0.20	ND
	7	9.7	0.06	0.17	ND
	14	9.6	0.06	0.18	ND
	28	9.8	0.04	0.22	ND
M-18	1	9.9	0.06	0.19	ND
	7	9.7	0.05	0.17	ND
	14	9.7	0.04	0.14	ND
	28	10.1	0.02	0.27	ND

Table 11
Leachate components of stabilized MSW fly ash by leachate tests set by the Environmental Agency, Japan

Symbol	pH	Leachate concentration (ppm)				
		Cd	Pb	Zn	Cr(VI)	As
M-13	9.8	0.08	0.33	0.03	ND	ND
	10.1	0.03	0.16	0.02	ND	ND

contribute any impact on the hardening mechanisms. From the XRD analysis, NaCl and KCl were detected in large quantities and ettringite was observed in a small quantity. Similar observation was noted in MSW fly ash samples stabilized with either cement or FCA.

6.2. Leachate characteristics of heavy metals

Leachate concentrations in heavy metals are shown in Table 10. The Cd leachate correlates to the pH value, similar to the MSW fly ash stabilized by cement. Therefore, the Cd could leach in high concentrations if FCA were used without cement. The criterion to assess the Cd leachate is that it should be judged as 9.0 in the pH value of the solution. This is similar to the results mentioned in Section 5 and consistent with the solubility chemistry. The leachate characteristics of Pb and Zn are also similar to those specimens stabilized separately by FCA and cement. It is suggested that the multiple use of FCA and cement results in effective containment of heavy metals.

Table 11 shows the leachate test results obtained through the method specified as per Environmental Agency, Japan (JLT-46). All test results cleared the leachate standard requirement of landfilling.

6.3. Soaking durability

The strength of MSW fly ash (stabilized with FCA and cement) decreased due to soaking, but remained high enough to be used as a geotechnical filling material as shown in Fig. 7. The heavy metals leaching into the soaked water is another major

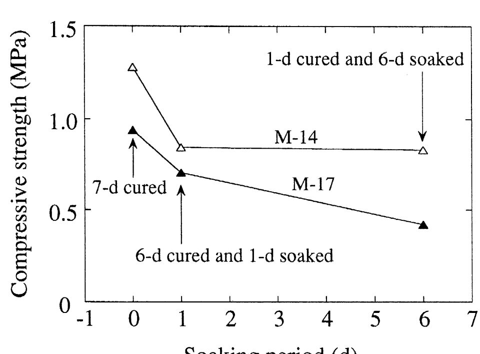

Fig. 7. Strength changes of stabilized MSW fly ash due to soaking.

Table 12
Leachate components in the soaked water

Symbol	Soaking period (days)	pH	Leachate concentration (ppm)		
			Cd	Pb	Zn
M-14	1	9.7	< 0.005	0.02	ND
	6	9.3	0.01	0.03	ND
M-17	1	9.9	ND	ND	ND
	6	9.6	< 0.005	0.03	ND

environmental concern. According to the test results shown in Table 12, the leachate concentrations of heavy metals are less and longer soaking periods result in less leachate of Cd. Therefore, it can be summarized that MSW fly ash stabilized with FCA and cement is safe from the view of leaching of heavy metals regardless of soaking or the groundwater conditions.

In order to evaluate the mechanisms of the soaking durability, changes in the mass of the soaked specimens and the salt content of the soaked water were measured. Also, an XRD analysis and SEM observations was conducted. The results are shown in Figs. 8–10. In the first stage of soaking, the salts dissolved in the soaked water and the mass of the specimens decreased. But in the following stage, appearance of cracks or fractures on the specimens, and increase in mass, volume, and the salt concentration of the soaked water were observed. The XRD analysis and SEM observations indicate that NaCl and KCl have leached from the stabilized ash during the first stage, and consequently, the cement component realized hydration to form some by-products, such as ettringite and

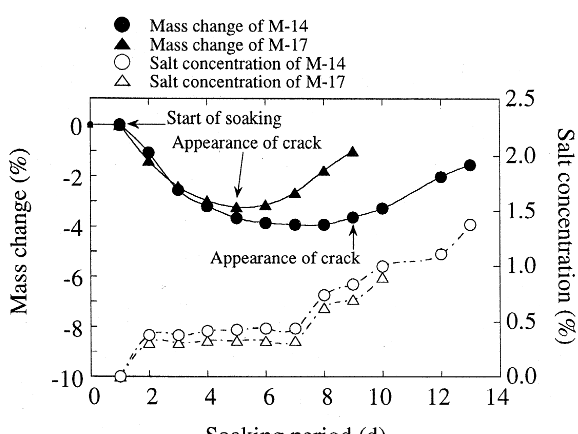

Fig. 8. Mass change of stabilized MSW fly ash and salt concentration of soaked water.

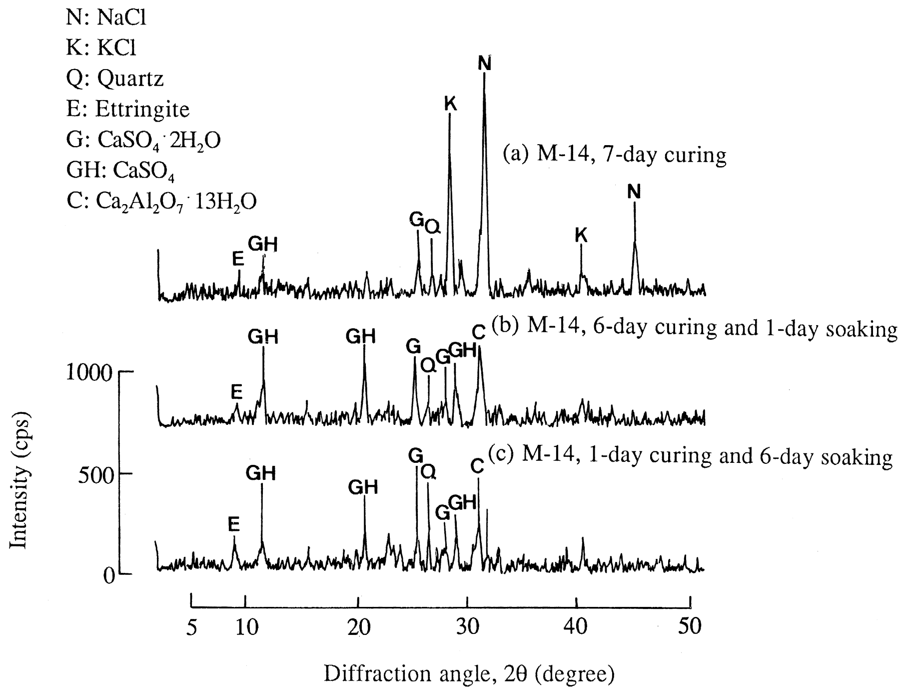

Fig. 9. The XRD patterns for MSW fly ash mixtures under soaking condition.

calcium aluminate hydrate (CAH; $CaO \cdot Al_2O_3 \cdot H_2O$). It can be concluded that the soaking durability is affected by salt leaching and hydration of cement components.

7. Possibility for geotechnical application

The experimental results aforementioned showed that the MSW fly ash can be sufficiently stabilized by cement and FCA. The gained strengths are considered to be

M-17, 1-day curing and 6 day soaking

Fig. 10. The SEM micrographs of stabilized MSW fly ash under soaking conditions.

high enough so that the mixture can be used in some geotechnical applications, such as embankment construction. Furthermore, the MSW fly ash stabilized with cement and FCA has a certain durability against soaking conditions. However, those leaching amounts are not negligible even though this stabilization method significantly decreases the leaching of heavy metals.

In view of possible geo-environmental contamination due to alkali, Kamon et al. [23] discussed the effectiveness of cover and filtration layers for embankments constructed with stabilized materials such as cement-stabilized soils and/or wastes. The soils and wastes stabilized with cement exhibit extremely high pH values due to the presence of $Ca(OH)_2$. Kamon et al. [23] reported that an appropriate thickness of the cover on the stabilized layer would minimize seepage into the stabilized layer, and consequently, the amount of alkaline seepage water which could affect groundwater would decrease. In addition, a sufficiently thick filtration soil layer, which should have a high alkaline adsorption capacity, beneath the stabilized layer would minimize the geo-environmental contamination due to alkali. Such findings may be applicable to heavy metals as well. Therefore, the MSW fly ash stabilized with cement and FCA might be suitable for embankment construction with appropriate cover and filtration layers.

8. Conclusions

In this paper, the stabilization of MSW fly ash with FCA was discussed from the standpoint of geotechnical applications. The main results can be summarized as follows.

(1) In the case of MSW fly ash stabilized with cement, the stabilization does not have enough effect on strength development and soaking durability. The addition of cement only contributes to the containment of heavy metals due to the high level of alkaline.

(2) When using FCA as a stabilizing agent for MSW fly ash, the mixture exhibits high strength and durability. However, the Cd leachate cannot be prevented in the early stages of curing.

(3) The multiple use of cement and FCA as an MSW fly ash stabilizer can attain strength development, high soaking durability, and containment of heavy metals. The method is effective for stabilizing MSW fly ash.

(4) The behavior of soluble salts contained in MSW fly ash can greatly affect strength development, soaking durability, and the hardening reaction of stabilized MSW fly ash mixtures.

(5) Stabilized MSW fly ash mixtures can be applied practically to road embankments and/or river dikes with cover soil in order to avoid additional leachate from MSW mixtures.

References

[1] M. Hiraoka, S. Sakai, The properties of fly ash from municipal waste incineration and its future treatment technologies, Waste Management Research, JSWME 5 (1) (1994) 3–17 (in Japanese).

[2] M. Kokado, Research on the treatment of fly ash from MSWI in Tokyo, Waste Management Research, JSWME 5 (1) (1994) 46–59 (in Japanese).
[3] T. Shimaoka, M. Hanashima, The behavior of fly ash stabilized by cement solidification in landfills, Waste Management Research, JSWME 5 (1) (1994) 32–45 (in Japanese).
[4] M.H. Maher, J.M. Butziger, Y.S. Chae, Utilization of municipal solid waste ash as a construction materials, in: M.A. Usmen, Y.B. Acar (Eds.), Environmental Geotechnology, Balkema, Rotterdam, 1992, pp. 457–466.
[5] J. Hartlen, Use of incinerator bottom ash as filling material, Proceedings of the Thirteenth International Conference on Soil Mechanics and Foundation Engineering, New Delhi Vol. 4 1994, pp. 1583–1586.
[6] J.R. Triano, G.C. Frantz, Durability of MSW fly ash concrete, Journal of Materials in Civil Engineering, ASCE 4 (4) (1992) 369–384.
[7] J.B.M. Hudales, The use of MWI fly ash in asphalt for road construction, in: J.J.J.M. Goumans, H.A. van der Sloot, Th.G. Aalbers (Eds.), Environmental Aspects of Construction with Waste Materials, Elsevier, Amsterdam, 1994, pp. 227–232.
[8] A. Gerdes, F.H. Wittmann, Use of ashes from MSW incineration in cementitous building materials, in: J.J.J.M. Goumans, H.A. van der Sloot, Th.G. Aalbers (Eds.), Environmental Aspects of Construction with Waste Materials, Elsevier, 1994, pp. 905–908.
[9] C.J. Poran, F. Ahtchi-Ali, Properties of solid waste incinerator fly ash, Journal of Geotechnical Engineering, ASCE 115 (8) (1989) 1118–1133.
[10] M. Kamon, T. Katsumi, Y. Sano, Stabilization of municipal waste incineration fly ash,Proceedings of the First National Symposium on Environmental Geotechnology, JGS, 1994, pp. 231–238 (in Japanese).
[11] M. Kamon, T. Katsumi, Utilization of coal fly ash from fluidized bed combustion systems, Geoenvironment 2000, in: Y.B. Acar, D.E. Daniel (Eds.), ASCE1995, pp. 1765–1779, Geotechnical Special Publication No. 46.
[12] M. Nishi, N. Yoshida, S. Kigoshi, H. Ohta, A. Maeda, Performance evaluation of coal ash treated subgrade in asphalt pavement, in: A.S. Balasubramanium, Yudbhir, D.T. Bergado, N. Phien-Wej, T.H. Seah, P. Nutalaya (Eds.), Prediction versus Performance in Geotechnical Engineering, Balkema, Rotterdam, 1994, pp. 85–94.
[13] C.B. Behr-Andres, N.J. Hutzler, Characterization and use of fluidized bed combustion coal ash, Journal of Geotechnical Engineering, ASCE 120 (6) (1994) 1488–1506.
[14] J. Rogbeck, P. Elander, Potentials for utilisation of PFBC ash, in: J.J.J.M. Goumans, H.A. van der Sloot, Th.G. Aalbers (Eds.), Environmental Aspects of Construction with Waste Materials, Elsevier, Amsterdam, 1994, pp. 589–598.
[15] K.K. Pandey, G.A. Canty, A. Atalay, J.M. Robertson, J.G. Laguros, Fluidized bed ash as a soil stabilized in highway construction,Geoenvironment 2000, in: Y.B. Acar, D.E. Daniel (Eds.), ASCE1995, pp. 1422–1436, Geotechnical Special Publication No. 46.
[16] H.A. van der Sloot, D.S. Kosson, T.T. Eighmy, T.N.J. Comans, O. Hjelmar, Approach towards international standardization: a concise scheme for testing of granular waste leachability, in: J.J.J.M. Goumans, H.A. van der Sloot, Th.G. Aalbers (Eds.), Environmental Aspects of Construction with Waste Materials, Elsevier, Amsterdam, 1994, pp. 905–908.
[17] T.T. Eighmy, H.A. van der Sloot, A unified approach to leaching behavior of waste materials, in: J.J.J.M. Goumans, H.A. van der Sloot, Th.G. Aalbers (Eds.), Environmental Aspects of Construction with Waste Materials, Elsevier, Amsterdam, 1994, pp. 905–908.
[18] IAWG (The International Ash Working Group), Municipal Solid Waste Incinerator Residues, Elsevier, Amsterdam, 1997.
[19] S. Tomizawa, K. Kamiya, M. Kawamura, S. Toyama, Chemical composition and leachate components of the MSW incinerated fly ash from electrostatic precipitator, Journal of Chemical Society Japan (7) (1979) 946–950.
[20] M. Tanaka, M. Osako, H. Kawamoto, H. Inagawa, Leachate of heavy metals from the MSW fly ash in landfill and its prevention, Proceedings of the 13th Environmental and Sanitary Engineering Research, Kyoto University, 1992, pp. 229–258 (in Japanese).
[21] M. Kamon, Re-use of by-products, in: P.S. Seco e Pinto (Ed.), Environmental Geotechnics Vol. 4 Balkema, Rotterdam, 1998, pp. 1279–1292.

[22] M. Kamon, S. Nontananandh, S. Tomohisa, Environmental geotechnology for potential waste utilization, Proceedings of the Ninth Asian Regional Conference on Soil Mechanics and Foundation Engineering, 1991, pp. 397–400.
[23] M. Kamon, T. Katsumi, C. Ying, Environmental quality assessment and control in geotechnical engineering, Proceedings of the Fourteenth International Conference on Soil Mechanics and Foundation Engineering Vol. 3 Balkema, Rotterdam, 1997, pp. 1827–1830.