Durability evaluation of coal ash mixed material on wetting and drying test 
considering the various environmental degradation factors

Takuro Fujikawa), Kenichi Sato ii) and Chikashi Koga iii)
i) Assistant Professor, Department of Civil Engineering, Fukuoka University, 8-19-1, Nanakuma, Jonan, Fukuoka, 814-0180, Japan.
ii) Professor, Department of Civil Engineering, Fukuoka University, 8-19-1, Nanakuma, Jonan, Fukuoka, 814-0180, Japan.
iii) Research assistant, Department of Civil Engineering, Fukuoka University, 8-19-1, Nanakuma, Jonan, Fukuoka, 814-0180, Japan.

ABSTRACT

It is important for coal fly ash and/or any other recycling materials to guarantee not only quality and safety of 
surround environment but also durability due to promoting the utilization. This study focused on the durability of 
coal ash mixed material which is made by cements, water, coal fly ash and soil. Also, this study focused on wetting 
and drying test as one of the durability test. This paper reports, 1) durability evaluation of coal ash mixed material on 
wetting and drying test, 2) assessment of the effect on the environment of coal ash mixed material considering the 
various environmental degrading factors. As a result, it was revealed that the compressive strength of coal ash mixed 
material that underwent wetting and drying decreases as degradation progresses regardless of the solutions. And the 
degradation mechanism depends on the type of solution of durability test.

Keywords: coal fly ash, wetting and drying test, cement stabilization, durability, unconfined compression test

1 INTRODUCTION

In Japan, the ratio of thermal power generation to 
power energy is increasing due to shutdown of a 
nuclear power plant after the great east Japan 
earthquake. Therefore, coal fly ash from thermal power 
plant is also increasing. Since the coal fly ash is 
established by the Law for Promotion of Effective 
Utilization of Resources as designated by-product, we 
have to observe the effective utilization for these 
by-products. However, utilization volume of coal fly 
ash is not advanced for public works, regardless of 
being developed as coal ash mixed material invented by 
Power Company, University and Construction 
Company (Japan Coal Energy Center 2011). One of 
the biggest reason the effective utilization of coal ash 
mixed material and recycle material have a relatively 
short history compared to its natural material. Moreover, 
the systematic framework and the testing method 
guaranteed material quality, safety and durability is not 
established for long periods. Therefore, it is very 
important for coal ash and other recycling materials to 
guarantee not only safety of surround environment but 
also long term durability in order to promote the 
effective utilization.

Purpose of this study is to establish the long term 
durability evaluation method of coal ash mixed material 
to extend the application, and to reveal the interaction 
between results of laboratory test and actual phenomenon. This paper reports that 1) durability 
evaluation of coal ash mixed material on wetting and 
drying test, 2) assessment of the effect on the environment of coal ash mixed material considering the 
various environmental degrading factors.

2 TESTING PROCEDURE

2.1 Preparation method of coal ash mixed material

Coal ash mixed material is a mixture of kaolin clay 
and coal fly ash, blast-furnace cement type B, and water. 
Table 1 shows the physical properties and chemical 
composition of the coal fly ash. Specimens were 
prepared by adjusting the water content of kaolin clay 
based on its liquid limit (3.5 times the liquid limit, i.e., 
w = 181.1%), and cement and coal fly ash were added 
as percentages of the wet weight of kaolin clay to 
obtain compressive strength \( q_u = 1000 \text{ kN/m}^2 \) after 
curing for 28 days. Specimens were prepared by mixing 
the constituent materials, stirring in a Hobart mixer for 
5 minutes, and casting the slurry in 5 cm \( \times \) 10 cm 
cylindrical molds according to the Practice for making 
and curing stabilized soil specimens without compaction (JGS 0821-2009). Unmolded specimens 
were wrapped with a thin plastic film and air cured at 
20 °C. Table 2 shows the experimental conditions.

2.2 Wetting and drying test

According to ASTM D4843 Wetting and drying tests 
were performed (Table 3). The specimens were 
dried in a drying oven at 60 ± 3 °C for 24 h and then
cooled in air at 20 ±3 °C prior to wetting. Subsequently, specimens were completely immersed and soaked for 23 hour in distilled water. Fifteen such wetting and drying cycles were applied. At the end of each cycle, the height, diameter, and mass of each specimen were determined, and specimen chips from the surface and the center were collected to be tested according to the Japanese leaching test No. 46 (JLT46).

Calcium ion (Ca) and heavy metals were analyzed using ICP plasma emission spectroscopy. In this study, the soundness evaluation method shown in Table 4 was used to visualize the degradation of the coal ash mixed material (Mori 2005). For sorting the unconfined compression strength data, the mean cross section area of the specimens was obtained by measuring the diameter at the top, middle, and bottom part of each specimen prior to the unconfined compression testing. Chipped or slightly damaged specimens were restored with jet cement.

### 3 RESULTS AND DISCUSSIONS

#### 3.1 Soundness evaluation of coal ash mixed material

Figure 1 shows the soundness evaluation procedure. To simulate deterioration, damages caused by sulfate acid rain on soil are considered. Acid rain and sulfate-containing soil caused by these rains are global problems. In general, coal ash mixed materials are protected during construction and do not come into direct contact with acid rain and soil sulfates. However, to better understand the worst case, such as damage of the protection material, acid rain and sulfate solutions with different concentrations are considered. In Case 1 (distilled water) and Case 2 (acid rain) specimens, cracks decreased soundness. However, the defects did not result in specimen breakage after 15 cycles. On the other hand, careful observations of the sulfate solutions in Case 3 (1% sulfate solution) and Case 4 (5% sulfate solution) allowed us to find that degradation progressed as the concentration of sulfates increased with maximal specimen deterioration and exfoliation in Case 4. The severe specimen exfoliation did not allow performing unconfined compression tests in these specimens after the fifth cycle. Apparently, exposure to sulfates affects the durability of coal ash mixed materials.

#### 3.2 Durability of coal ash mixed material

Figure 2 shows the relation between the number of cycles and the strength normalized with the zeroth unconfined compressive strength. The characters in the figure denote the soundness rankings. The compressive strength of the coal ash mixed material, regardless of the type of solutions, increased in the early cycles, peaked around the seventh cycle, and decreased afterward. The early strength increase is attributed to the acceleration of the hydration owing to the high-temperature curing during the drying and water
immersion stage. The late strength reduction is attributed to the elution of Ca following the degradation of specimens or to dissolution owing to the diffusion of Ca cations with increasing number of cycles. As degradation overcomes strength, the unconfined compressive strength starts to decrease. After the seventh cycle, the strength of Case 2 specimens is generally lower than that of Case 1 specimens, whereas Case 3 and Case 1 specimens show similar behavior. However, the strength of Case 3 specimens rapidly drops after the tenth cycle.

Figure 3 shows the relation between the number of cycles and the expansion–contraction ratio, which denotes the variation in the specimens’ length in the vertical direction; positive values represent shrinkage. Case 1 specimens have constant expansion–contraction ratio, whereas Case 2 specimens shrink. Case 3 specimens show expansion when the compressive strength starts to decrease. The expansion is attributed to ettringite precipitation from the solutions. It is known that excessive ettringite precipitation causes strength reduction (Kamon 1991). The fact that severe exfoliation occurred in Case 4 specimens supports the argument that the expansion of specimens is due to ettringite, which also causes specimen degradation and strength reduction. Figure 4 shows the relation between the number of cycles and the variation in mass. Each case is represented by two lines. The line with filled symbols and the line with blank symbols show the change in mass after the wetting and drying stage, respectively. All cases show little change in mass after wetting. Case 2 and 3 specimens show greater differences in mass after drying and wetting than Case 1, which implies higher porosity and increased water inflow and outflow in the specimens. The trend is especially apparent in Case 3. Figure 5 shows the relation between the number of cycles and Ca content. Ca content tends to decrease as the number of cycle increases, especially in Case 3 and Case 4 that exhibit higher degradation and Ca content decrease. Thus, the degradation mechanism of the coal ash mixed material that underwent wetting and drying is attributed to drying contraction or volume expansion with increasing number of wetting and drying cycles and increasing porosity or slaking subsequent to mass change. It was revealed that these degradation factors facilitate the elution of Ca. Therefore, it is necessary to take appropriate measures during construction works in sulfate-rich soils.
3.3 Evaluation of environmental impact on specimens that suffered various environmental degradations

In this study, the heavy metals targeted in the leaching tests are hexavalent chromium, fluorine, and boron. In all cases, hexavalent chromium was less than the limit of quantification, and fluorine and boron were less than standard limiting values. Therefore, only fluorine is examined. Figures 6 and 7 show the concentration of eluted boron at the surface and center of the specimens, respectively, as a function of the number of cycles. The concentration of boron is generally higher in the center than the surface, which suggests that degradation starts at the surface. Moreover, at the surface, the concentration of boron tends to decrease with increasing number of cycles in all cases. As also inferred from Figure 8, which shows the relation between the accumulated filtrate concentration (mg/kg) and the number of cycles, the replacement of the solution at the end of every cycle maintains the concentration gradient between the specimens and the solution, causing the elution of components. Thus, the concentration of the eluted components in the specimens decreases, whereas the accumulated amount of eluted components increases.

From the observations, the degradation apparently progresses with repeated wetting and drying cycles and considerably affects the elution properties of coal ash mixed material. However, the possibility of excessive leaching that exceeds soil environment standards (B: 1.0 mg/L) is low.

4 CONCLUSIONS

The results of this study are summarized as follows:
1) The compressive strength of coal ash mixed material that underwent wetting and drying decreases as degradation progresses regardless of the solutions.
2) The degradation mechanism depends on the type of solution. Drying contraction is seen in acidic rain solutions, whereas exfoliation owing to expansion is seen in sulfate solutions. The degradation of coal ash mixed material exposed to sulfate solutions is particularly strong and depends on the sulfate concentration.
3) The degradation owing to repeated wetting and drying cycles considerably affects the elution properties of the coal ash mixed material. However, the possibility of excessive leaching that exceeds environmental standards is low.

REFERENCES

1) Imanishi, H., Kamon, M., and Katsumi, T. (1991): Durability of cement-treated soils under repeated wetting and drying cycles, CAJ Proceedings of Cement & Concrete, No.45, 744-749 (in Japanese).
2) Kumakura, K., Mori, M., and Takahashi, H. (2005): An Experimental Study on the Durability of Fiber-Cement-Stabilized Mud by Repeated Cycle Test of Drying and Wetting, Shigen-to-Sozai, Vol. 121, 37-43 (in Japanese).
3) Standard Test Method for Wetting and Drying Test of Solid Wastes (2009), Designation: D4843-88, ASTM International.
4) Japan Coal Energy Center (2011), Effective utilization guideline of coal ash mixed material on port construction work 2011 (in Japanese).