Long-term properties of coal ash embankments

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ABSTRACT

Technologies for the effective use of coal ash generated from coal power plants as construction materials have been making great progress due to growing interest in achieving a sustainable materials-cycling society. However, among the different kinds of coal, which is the raw material of coal ash, there are those that elute hazardous substances in excess of the environmental soil quality standards. To control the elution of such hazardous substances, coal ash is solidified. There are few examples which have investigated change in the amount of hazardous substance elution, or intensity over a long period of time with respect to coal ash solidified with cement. Thus, the authors have been continuously measuring the strength of embankments made from solidified coal ash and the elution quantities of hazardous substances. Such measurements show that, in some cases, the strength of solidified coal ash decreases in the long term. It is also found that solidification can lower the levels of some hazardous substances to below the environmental standard value. However, it is also found that even with solidification, elution quantities of some of hazardous substances can exceed the standard value over time.

Keywords: coal ash, hazardous substance, civil engineering material, solidification, Long-term strength

1 INTRODUCTION

The properties of coal ash generated from coal power plants differ in accordance with the properties of the coal that is the raw material of coal ash, the types of boilers that combust the coal and the combustion temperature. In view of these different properties, coal ash has often been used effectively as a construction material. However, there are kinds of coal that contain hazardous substances. Coal ash generated as a result of the combustion of such coal can also contain hazardous substances in quantities exceeding the environmental standard values. The solidification of coal ash after the addition of cement is one measure to prevent the elution of hazardous substances. In this study, the strengths of solidified slurried coal ash that was used as a construction material more than 20 years ago and of embankments constructed from granulated coal ash more than 10 years ago were studied, and the elution and content of hazardous substances were measured as well. This report is a summary of the above-mentioned study results.

2 STUDY METHOD

For coal ash that was used for bridge or embankment construction, changes in strength over time and elution quantities of hazardous substances were measured. Measurements of the elution quantities of hazardous substances into the surrounding environment were based on Environment Agency Notification No. 46 (Ministry of the Environment, 1991), and measurements of the content of hazardous substances were based on Environment Agency Notification No. 19 (1994). It is known that due to the coal ash generation process, some organic substances in coal ash are decomposed. Thus, from 27 substances for which environmental standards of soil elution and soil content are set for survey by the above-mentioned environmental agency notifications, the 8 substances of total mercury, lead, hexavalent chromium, cadmium, arsenic, selenium, boron and fluorine were selected for measurements of the elution quantities from and the content in coal ash. Solidified slurried coal ash and embankments made from granulated coal ash were the study materials.

2.1 Solidified slurried coal ash

Solidified slurried coal ash was used as an embankment material for the artificial island in the construction of the Hakacho Ohashi Bridge along National Highway 37 in Muroran City (Watanabe Isao
et al., 1989, Goto Hiroyuki et al., 1989). This is a suspension bridge with a center span of 720 m, a side span of 330 m and a total length of 1380 m. For the construction of a main tower that supports a main cable of a suspension bridge, an artificial island is required as a construction yard. A conventional method for the construction of an artificial island that functions as the foundation of a main tower is to use steel sheet pilings or steel pipe sheet piles for cofferdam construction and to put soil into the cofferdam as an embankment material. However, the construction site of Hakuco Ohashi Bridge was relatively deep underwater, at a depth of 14 m to 17 m; therefore, the use of soil as an embankment material would have applied high earth pressure, which would have necessitated a very large-scale cofferdam. In view of the above, slurried coal ash was used as a embankment material for the artificial island, because it can be placed underwater, it can stand alone after solidification during placement, and it applies less earth pressure to the cofferdam. Up to 2 years after its placement as an embankment material, the strength of the solidified slurried coal ash was measured by using samples taken at the time of placement onsite. The samples were cured for the prescribed periods before measurements. Two years after the use of the ash as an embankment material, bridge piers were constructed and excavation work took place inside of the artificial island. Samples taken during the above excavation work were used after curing for the prescribed periods, to measure the strength of the solidified slurried coal ash from 2 years after its use onward. Solidified slurried coal ash was sampled in blocks from the excavation site. Then from each block of the ash, a cylindrical core was taken out of 5 cm in diameter and 10 cm in height and was cured indoors under constant temperature and humidity (at a long period of time. The samples were individually temperature of 20 °C and a humidity of 80 %) for a wrapped to prevent neutralization caused by aridity and carbonic acid gas.

The raw materials of the slurried coal ash were coal ash generated from the Tomakomai Thermal Power Plant of the Hokkaido Electric Power Co., Inc., volcanic ash from around Muroran City, ordinary Portland cement and seawater. Basic physical properties of volcanic ash and coal ash used for making slurried coal ash are shown in Table 1. Six types of coal ash, from A to F, were used. The table shows the ranges of values of basic physical properties of coal ash. Both volcanic ash and coal ash have smaller soil particle density than that of general soil particles. Of the several types of coal ash used, the component compositions of some are known, and they are shown in Table 2. Slurried coal ash is made from coal ash and volcanic ash mixed at a ratio of 7:3 (dry weight), cement (added in a weight of 4 to 5 % of the total weight of the mixture) and seawater. Conditions for mixing raw materials to prepare each sample are shown in Table 3. Samples of slurried coal ash were prepared with a slump of 8-13 cm to secure fluidity at the time of placement as an embankment material, with a target unconfined compressive strength of 500 kN/m² after 7 days, 650 kN/m² after 28 days and 1100 kN/m² after 91 days of placement.

Unconfined compressive strength was checked 7

| Slurry No. | Type of coal ash | Average depth of placement (m) | Cement moisture content (%) | Slump (cm) | Bleeding (%) |
|-----------|------------------|--------------------------------|-----------------------------|------------|-------------|
| 1         | A                | 0.5                            | 4                            | 40         | 11.1        | 1.2         |
| 2         | B                | 1.5                            | 5                            | 35         | 10.8        | 1.1         |
| 3         | B                | 2.5                            | 5                            | 35         | 9.0         | 0.7         |
| 4         | C                | 3.5                            | 5                            | 50         | 10.3        | 1.3         |
| 5         | D                | 4.5                            | 5                            | 60         | 10.9        | 3.5         |
| 6         | B                | 5.5                            | 5                            | 35         | 10.0        | 0.8         |
| 7         | E                | 2.5                            | 5                            | 35         | 9.0         | 0.7         |
| 8         | E                | 7.0                            | 4                            | 50         | 9.8         | 3.4         |
| 9         | F                | 8.0                            | 4                            | 50         | 10.5        | 1.3         |
| 10        | E                | 9.0                            | 5                            | 35         | 10.8        | 0.7         |
| 11        | C                | 10.5                           | 4                            | 55         | 9.3         | 2.9         |
| 12        | C                | 12.0                           | 5                            | 40         | 10.4        | 2.3         |

Table 2. Component compositions of coal ash used to prepare slurried coal ash (Kawaguchi Masato et al., 2005)

| Types of coal ash | Slurry No. | SiO₂ | Al₂O₃ | Fe₂O₃ | TiO₂ | CaO | MgO | Na₂O | K₂O | P₂O₅ | SO₃ |
|------------------|------------|------|-------|-------|------|-----|-----|------|------|------|-----|
| A                | 1          | 70.3 | 23.0  | 1.3   | 1.1  | 0.7 | 0.3 | 0.1  | 2.3  | 0.1  | 0.3 |
| B                | 2,3,6      | 54.3 | 17.8  | 16.5  | 0.8  | 3.9 | 1.3 | 0.3  | 1.0  | 0.2  | 2.6 |
| E                | 7,8,10     | 60.6 | 18.5  | 4.2   | 0.8  | 9.2 | 1.2 | 0.9  | 0.6  | 0.3  | 3.7 |
days, 28 days, 2 years, 10 years, 15 years and 20 years after placement. In addition, the elution quantities of hazardous substance were checked 15 years and 20 years after placement, and the contents of hazardous substances were checked 20 years after placement.

2.2 Embankments made of granulated coal ash

When coal ash generated from a coal thermal power plant contains fine particles in large quantity, they disperse during embankment construction and adversely affect the surrounding environment. One countermeasure is to granulate the coal ash that is to be used as an embankment material. In view of the above, granulated coal ash with basic physical properties shown in Table 4 was prepared and used for embankment construction in 2001 (Embankment No. 1), in 2002 (Embankment No. 2) and in 2004 (Embankment No. 3). The embankment designs are shown in Figure 1. Coal ash was granulated by a batch-type revolving granulator after the addition of the prescribed quantity of water to pulverulent coal ash. Coal ash used for Embankments No. 1 and No. 2 contained oxidized calcium accounting for 10% of the total weight, because it was emitted from a boiler that uses limestone to remove sulfur generated during combustion. Therefore, solidification was carried out by adding water. Coal ash in Embankment No. 3 does not solidify with the addition of water. Therefore, cement was added for granulation. In both cases, coal ash was used for embankment construction after it was granulated and cured for a prescribed period of time at room temperature. Embankments were constructed with a width of 4.0 m, a side-slope gradient of 1:1.5, a height of 2.0 m and a length of 6.0 m, and with a finished thickness per layer of 30 cm. Table 4 also shows certain qualities of each embankment at the time of construction.

The strengths of embankments of granulated coal ash were measured for several years after construction by

![Fig. 1. Designs of embankments made of granulated coal ash](image-url)
Swedish penetration test. The elution quantities and the contents of hazardous substances were also studied.

3 STUDY RESULT

3.1 Solidified slurried coal ash

3.1.1 Temporal changes in unconfined compressive strength

Figure 2 shows the relation between the passage of time after the placement of solidified slurried coal ash as an embankment material and the unconfined compressive strength of the ash. Excluding No. 4, the unconfined compressive strengths of all types of solidified slurried coal ash increased with time up to the passage of 10 years. After that, the strengths of some types further developed up to the passage of 15 years, but after 20 years, the unconfined compressive strengths of all samples were lower than their peak values. The strengths of No. 4 and No. 5 at 28 days were no less than the target value of 650 kN/m². However, at 2 years, the strengths never exceeded the 91st-day target value of 1100 kN/m². Some of the different types of coal ash did not greatly develop strength in the long term, although strength development was observed at the initial stage. The overall trend was for strength to first increase over time and then to decrease at a later stage. In the future, we intend to confirm the relation between the passage of time and strength by the measurement of oxidized calcium quantity and the like.

It should be noted that when Coal Ashes A, B and E, content is lower than that of B (No. 2, 3 and 6). This is in line with the report that CaO content affects strength (Suzuki Kazuo et al., 1987).

3.1.2 Influence on the environment

Hazardous substances in solidified slurried coal ash

are shown in Table 5. Among measured hazardous substances, only those that have values within the accuracy of measurement are shown in the table. Values of the elution quantities or the contents of hazardous substances below the measurement range are not listed in the table. The elution quantities of boron exceeded the standard value in most samples after 15 years. After 20 years, the elution quantities were even greater than those after 15 years for more than half of the measured samples. No elution of arsenic was confirmed in any of the samples after 15 years, but after 20 years, its elution in some of the samples exceeded the standard value. Hexavalent chromium did not exceed the standards of water bottom sediments and elution set by the Law Relating to the Prevention of Marine Pollution and Maritime Disaster. The elution of hexavalent chromium showed a tendency to decrease with time. No hazardous substances exceeded the standards of water bottom sediments and contents set by the Law Relating to the Prevention of Marine Pollution and Maritime Disaster. It should be noted that

| Soil elution | Soil contents |
|--------------|---------------|
| Hexavalent chromium | After 15 years | After 20 years |
| Boron | mg/l | mg/kg |
| Hexavalent chromium | Boron | Arsenic | Selenium | Fluorine | Cadmium | Lead | Hexavalent chromium | Arsenic | Total mercury | Selenium | Fluorine | Boron |
| 0.04 | 2.4 | 0.01 | 3.5 | 0.009 | 0.001 | 0.1 | 0.2 | 13 | <0.5 | 17 | 0.32 | 1.1 | 60 | 5.3 |
| 0.02 | 1.4 | 0.01 | 1.9 | 0.01 | 0.003 | <0.1 | 0.15 | 5.8 | <0.5 | 12 | 0.21 | 0.93 | 46 | 3.1 |
| 0.01 | 1.3 | 0.01 | 1.3 | 0.008 | 0.002 | <0.1 | 0.14 | 9.7 | <0.5 | 6.2 | 0.07 | 1 | 47 | 2.7 |
| 0.01 | 2.4 | <0.01 | 0.24 | 0.007 | 0.001 | <0.1 | 0.13 | 9.7 | <0.5 | 9.2 | <0.04 | 0.86 | 26 | 0.46 |
| 0.02 | 1.0 | <0.01 | 0.94 | 0.007 | <0.001 | <0.1 | 0.22 | 10 | <0.5 | 9.6 | <0.04 | 0.08 | 30 | 1.4 |
| 0.02 | 1.6 | 0.01 | 1.4 | 0.008 | 0.004 | <0.1 | 0.14 | 8.9 | <0.5 | 23 | 0.22 | 0.96 | 48 | 2.8 |
| 0.02 | 2.5 | 0.01 | 3.9 | 0.005 | 0.003 | 0.3 | 0.26 | 16 | <0.5 | 16 | <0.04 | 0.94 | 88 | 5.7 |
| 0.03 | 2.4 | 0.01 | 4.2 | 0.028 | 0.001 | 0.3 | 0.26 | 16 | <0.5 | 16 | <0.04 | 0.74 | 73 | 6.1 |
| 0.01 | 0.3 | 0.01 | 1.9 | 0.02 | 0.005 | 0.20 | 0.17 | 11 | <0.5 | 15 | <0.04 | 2.8 | 29 | 0.52 |
| 0.03 | 2.4 | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 0.01 | 1.4 | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 0.05 | 1 | 0.05 | 1 | 0.01 | 0.01 | 0.8 | - | - | - | - | - | - | - | - |

* Standard of water bottom sediment set by the Law Relating to the Prevention of Marine Pollution and Maritime Disaster
* * Standard of soil elution
* *** Standard of soil contents of hazardous substances

\( ^{(*)} \) means the value is below the measurement accuracy.

Fig. 2. Passage of time vs. unconfined compressive strength (solidified slurried coal ash)
when solidified slurried coal ash was used for bridge construction, these environmental quality standards were not established yet.

3.1 Embankments made from granulated coal ash

3.2.1 Passage of time and embankment strength

Figure 3 shows the relation between the required number of half turns per meter of penetration and the depth in Embankments No. 1, 2 and 3 in the Swedish penetration test. The required numbers of half turns at the time of construction were measured for Embankments No. 1 and 2, and overall it was about 200 half turns. The overall tendency of Embankments No. 1 and 2 was for the possible depth of penetration to decrease with time, although it increased at some measurement periods. This indicates that the solidification of granulated coal ash progresses with increase in vertical load. It should be noted that the strengths of Embankments No. 1, 2 and 3 did not decrease after the passage of 7 years, 6 years and 4 years, respectively. Given that the strength of the solidified slurried coal ash decreased from the 10th year after use for bridge construction, we would like to continue measuring the strength of granulated coal ash.

The slope of Embankment No. 1 is shown in Fig. 4. A is where plant seeds were sprayed after soil dressing of the embankment surface, and B is where plant seeds were sprayed without soil dressing of the embankment surface. In B, no vegetation is observed even 11 years after embankment construction. At the same test site, another embankment made from materials other than coal ash was constructed. No seeds were artificially planted on the slope of this embankment, but airborne seeds were dispersed onto the embankment from the surrounding area, resulting in the growth of vegetation. This indicates that the slope of an embankment made from coal ash is not a suitable environment for vegetation growth. This is believed to be due to the fact that coal ash has no nutrients and is high in strength and pH value, which are unsuitable conditions for vegetation growth. In the case of A, seeds were sprayed after the slope of granulated coal ash was dressed with black earth of 30cm in thickness. It can be observed that A is fully covered with vegetation now at 11 years after embankment construction. These results show that the greening of coal ash embankments requires that they be covered with materials suitable for vegetation growth or that greening foundation materials be used.

3.2.2 Influence on the Environment

Hazardous substances in embankments made from granulated coal ash are shown in Table 6. The elution quantities of hazardous substances were below standard value in all embankments at the time of construction. Then, in Embankment No. 1, the elution of fluorine and boron exceeded the standard value in the 5th and 11th years, and that of selenium exceeded standard value in the 7th year. In Embankment No. 2, the elution of fluorine exceeded the standard value in the 2nd year, and that of boron exceeded standard value from the 4th year onward. In Embankment No. 3, the elution of fluorine exceeded the standard value in the 1st, 2nd and 4th years, that of boron from the 1st year onward, and that of selenium in the 2nd and 8th years. These results indicate that some hazardous substances, such as cadmium, lead, hexavalent chromium, total mercury and arsenic, hardly elute over time, whereas selenium, fluorine and boron do elute and their elution quantities...
increase with time. Contents of all hazardous substances were below the standard value.

From these results, it can be said that since hazardous substances in coal ash are closely related to the types of coal combusted, careful attention should be paid to hazardous substances in coal ash and to types of coal when coal ash is to be used as a construction material. When coal ash does not meet the environmental quality standard, measures should be taken, such as covering with soil.

4 CONCLUSIONS

The results of this study can be summarized as stated below:

(1) Solidified coal ash tends to decrease in strength after the passage of more than 15 years.

(2) Embankments made from granulated coal ash tend to increase in strength until the passage of about 10 years.

(3) Elution quantities of some hazardous substances exceed the standard value over time; thus, careful attention should be paid to hazardous substances in coal ash when coal ash is to be used as a construction material. When coal ash does not meet the environmental quality standard of the site where it is to be used, measures should be taken, such as covering with soil to prevent elution.

In conclusion, this study revealed that some properties of processed coal ash, such as strength and elution of hazardous substances, change with time. Until now, when using coal ash, the production place and quality of coal before combustion are understood. Sufficient investigation is conducted in advance regarding coal ash, and the amount of elution of a hazardous substance is checked. When elution is checked, the measure to prevent solubility of a hazardous substance and ensuring coal ash does not escape are needed. A tendency for strength reduction has been observed for 15 years or more since implementing the use of coal ash in construction. Therefore, it would be prudent to continue to measure strength reduction over a longer period until it reaches a safe level.

REFERENCES

1) Goto Hiroyuki, Miura Satoshi, and Watanabe Isao (1989): Filling Work for Artificial Island Construction of Hakuro Ohashi Bridge by Slurried Coal Ash, 32nd Technical Research Workshop of Hokkaido Regional Development Bureau, 179-184 (in Japanese).

2) Kawaguchi Masato, Ogawa Shigemichi, Horiiuchi Sumio, Nishimoto Satoshi, Sato Atsuko and Butsuda Rie (2005): Assessment of Long-term Environmental Adaptation of Ground Reclaimed by Slurried Coal Ash Method, Proceedings of the 40th Japan National Conference on Geotechnical Engineering, 667-668 (in Japanese).

3) Matsuda Masahiro, Nishimoto Satoshi and Sato Atsuko (2003): Construction of Embankment by the Use of Granulated Coal Ash. Proceedings of the 25th Japan Road Congress, (in Japanese).

4) Nishimoto Satoshi, Sato Atuko, Kido Yuichiro, Horiiuchi Sumio and Kawaguchi Masato (2006): Long-term Strength of Solidified Slurried Coal Ash, Proceedings of the 41th Japan National Conference on Geotechnical Engineering, 547-548 (in Japanese).

5) Notification No. 46 of the Ministry of the Environment (1991): Environmental Quality Standards for Soil Contamination, Ministry of the Environment.

6) Suzuki Kazuo and Matsushita Keirou (1989): Use of Coal Ash as Construction Materials. 426th Issue of Study Report by Hokkaido Electric Power Co., Inc. (in Japanese).

7) Watanabe Isao, Miura Satoshi and Yamazaki Tatsuya (1989): Use of slurried coal ash for artificial island construction of the Hakudo Ohashi Bridge, Proceedings of Annual Meeting of Tohoku Branch, JSCE, No.46, 685-690 (in Japanese).

8) Yamazaki Tatsuya, Noto Shigeyuki, Kajiya Yasuhiro and Abo Ryuichi (1988): Experiment on Composition of Embankment Material (Slurried Coal Ash) for Artificial Island of Hakudo Ohashi Bridge. Technical Report of the Annual Meeting of the Hokkaido Branch, vol.28, 39-46 (in Japanese).