Journal of Geoscience and Environment Protection, 2015, 3, 31-43
Published Online June 2015 in SciRes. http://www.scirp.org/journal/gep
http://dx.doi.org/10.4236/gep.2015.34005

Utilization of Coal Ash as a Barrier Material for Radioactive Waste Disposal

Takashi Sasaoka, Wahyudi Sugeng, Hideki Shimada

Department of Earth Resources Engineering, Kyushu University, Fukuoka, Japan
Email: sasaoka@mine.kyushu-u.ac.jp

Received 15 May 2015; accepted 21 June 2015; published 26 June 2015

Abstract

About 10% of total electricity (386 MkW) was generated by nuclear power plants in the world (2014) and about 58,400 tons of uranium has been mined in uranium mines annually. A plenty of radioactive waste material is produced from uranium mines and nuclear power plants. The wastes must be disposed or stored safely for a long term. Because if they leak and/or move from disposal or storage sites due to air/groundwater flow, then a serious environmental pollution can occur. Hence, multi-layer system has been proposed and employed in order to seal off these radioactive waste materials from biosphere. Basically, bentonite is now used for establishing one of absorbing and sealing layers in this system. However, the amount of high quality bentonite is very limited and in some cases it is hard to be obtained. On the other hand, a great deal of refuse from coal burning plants is produced every year and the amount of it is expected to be higher each year especially in developing countries. More than half of coal ash is utilized and the remaining is disposed at the disposal sites. However, the life of the disposal site is limited and it is difficult to find a new disposal site. It is requested that the percentage of the utilization of the coal ash be increased in every field. From the above two points of view, a fly ash-based barrier system is considered in this research and this paper discusses the applicability of fly ash as a content of barrier material. Based on the results of a series of laboratory tests, it can be concluded that fly ash has a potential for use in the buffer material as the bentonite is substituted.

Keywords

Utilization of Coal Ash, Radioactive Waste Disposal, Bentonite, Laboratory Tests

1. Introduction

Considering the situation of energy demand in the world, nuclear power generation might be growing up from now on. About 11% of total electricity (386 GW) was generated by nuclear power plants in the world (2014)

How to cite this paper: Sasaoka, T., Sugeng, W. and Shimada, H. (2015) Utilization of Coal Ash as a Barrier Material for Radioactive Waste Disposal. *Journal of Geoscience and Environment Protection*, **3**, 31-43.
http://dx.doi.org/10.4236/gep.2015.34005

and about 58,400 tons of uranium has been mined in uranium mines annually [1]. A plenty of radioactive waste material such as overburden, waste rocks and tailing materials is produced in uranium mines due to the mining operation, milling and uranium refinement. Radioactive waste is also a byproduct from nuclear reactors, fuel processing plants, and institutions such as hospitals and research facilities [2]. Since the only way that radioactive wastes finally become harmless is through decay, which for some isotopes contained in high-level wastes can take hundreds of thousands of years, the wastes must be stored in a way that provides adequate protection for very long times. Because if they leak and/or move from disposal or storage sites due to air/groundwater flow, then a serious environmental pollution can occur. Hence, multi-layer system has been proposed and employed in order to seal off these radioactive waste materials from biosphere [3]. Basically, bentonite is now used for establishing one of absorbing and sealing layers in this system. However, the amount of high quality bentonite is very limited and in some case it is hard to be obtained.

On the other hand, a great deal of refuse from coal burning plants is produced every year and the amount of it is expected to be higher each year especially in developing countries. More than half of fly ash is utilized and the remaining is disposed at the disposal sites. However, the life of the disposal site is limited and it is difficult to find a new disposal site. It is requested that the percentage of the utilization of the fly ash be increased in every field.

From the above points of view, a fly ash-based barrier layer/cover system instead of bentonite-only one is proposed in this research. This paper describes the current system and technology for radioactive waste disposal and then proposes and discusses the applicability of fly ash as a content of barrier layer/cover material based on the results of a series of laboratory tests.

2. Radioactive Waste Material and Disposal System

The Nuclear Regulatory Commission separates wastes into two broad classifications: high-level or low-level waste (NRC, 2010). High-level radioactive waste results primarily from the fuel used by reactors to produce electricity. Low-level radioactive waste results from uranium mine and reactor operations and from medical, academic, industrial, and other commercial uses.

2.1. High-Level Radioactive Waste Management

High-level radioactive wastes are the highly radioactive materials produced as a by product of the reactions that occur inside nuclear reactors [4]. Reprocessing extracts isotopes from spent fuel that can be used again as reactor fuel. Because of their highly radioactive fission products, high-level waste and spent fuel must be handled and stored with care. Since the only way radioactive waste finally becomes harmless is through decay, which for high-level wastes can take hundreds of thousands of years, the wastes must be stored and finally disposed of in a way that provides adequate protection of the public for a very long time.

High-level waste will be disposed of in a stable geological formation at a depth of more than 300 meters. The vitrified waste in fabrication canisters will be encapsulated in strong metal containers (overpacks) and, once emplaced in the repository, will be surrounded by a clay/bentonite buffer material. The canisters, overpacks and clay/bentonite buffer material are referred to as the engineered barrier system. The geological environment, which isolates the waste for long time periods, is termed the natural barrier. The multi-barrier system used for safe waste disposal is a combination of engineered and natural barrier. Research and development on the multi-barrier system will continue with a view to building confidence in this concept [5]. **Figure 1** shows the schematic of high-level radioactive waste disposal facility.

2.2. Low-Level Radioactive Waste Management

Low-level waste includes items that have become contaminated with radioactive material or have become radioactive through exposure to neutron radiation. This waste typically consists of contaminated protective shoe covers and clothing, wiping rags, mops, filters, reactor water treatment residues, equipment and tools, luminous dials, medical tubes, swabs, injection needles, syringes, and laboratory animal carcasses and tissues. The radioactivity can range from just above background levels found in nature to very highly radioactive in certain cases such as parts from inside the reactor vessel in a nuclear power plant. Low-level waste is typically stored on-site by licensees, either until it has decayed away and can be disposed of as ordinary trash, or until amounts are large enough for shipment to a low-level waste disposal site in containers. **Figure 2** illustrates the schematic of low-level radioactive waste disposal facility.

2.3. Uranium Mill Tailings

Uranium mill tailings are primarily the sandy process waste material from a conventional uranium mill [6]. This ore residue contains the radioactive decay products from the uranium chains (mainly the U-238 chain) and heavy metals. The tailings or wastes produced by the extraction or concentration of uranium or thorium from any ore processed primarily for its source material content is by product material. This includes discrete surface waste resulting from uranium solution extraction processes, such as in situ recovery, heap leach, and ion-exchange. By product material does not include underground ore bodies depleted by solution extraction. The wastes from these solution extraction facilities are transported to a mill tailings impoundment for disposal. Thick earthen covers is constructed in order to protect it by rock and designed to prevent seepage into ground water, over the

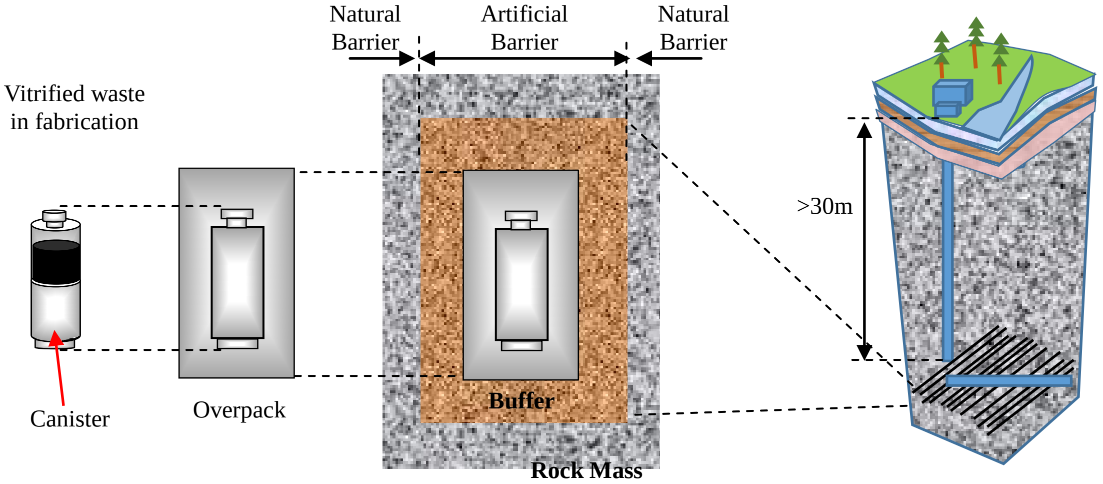


Figure 1. Schematic of high-level radioactive waste disposal facility.

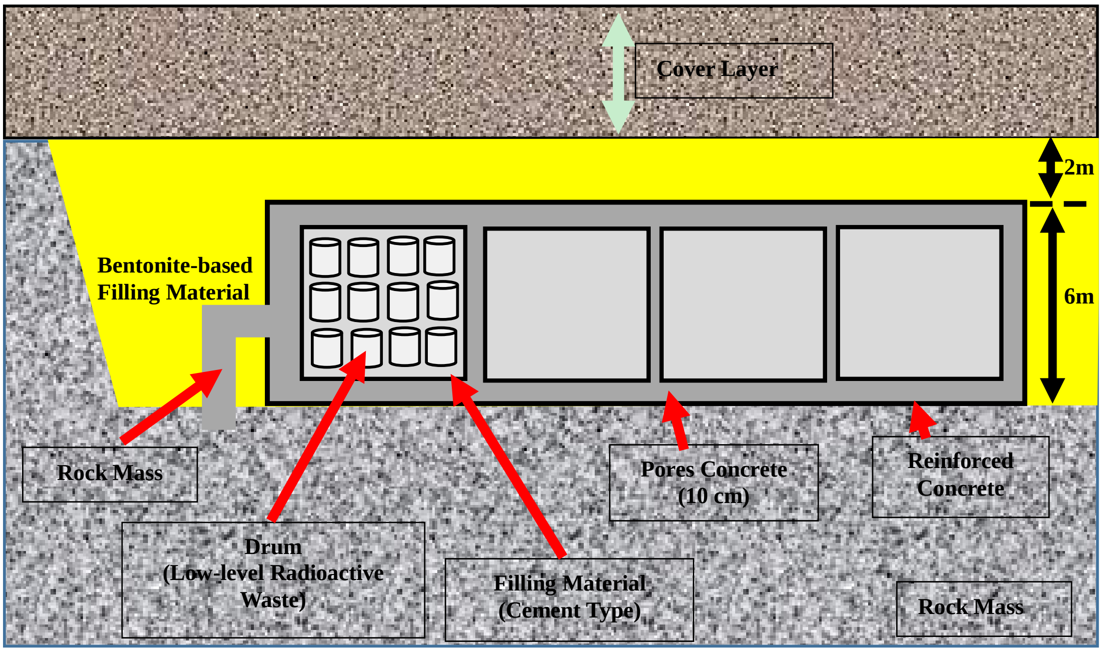


Figure 2. Schematic of low-level radioactive waste disposal facility.

waste. Earthen covers also effectively limit radon emissions and gamma radiation and, in conjunction with the rock covers, serve to stabilize the piles to prevent dispersion of the tailings through erosion or intrusion. In some cases, piles may be moved to safer locations. **Figure 3** illustrates the schematic of dumping site in uranium mine.

3. Utilization of Coal Ash

3.1. Coal Ash Utilization in Japan

Considering the expansion of coal utilization, it is necessary to promote the development of highly efficient coal and coal ash utilization technologies [7]. In Japan, coal ash production has been increasing and in FY2007, about 10 million tons of coal ash was produced. However, the issue is not only the level of coal ash produced but also the effective availability of coal ash utilization that gradually increases every year. This means that effective coal ash utilization technology has steadily improved in Japan over the past decade. Total coal ash utilization in FY2007 was 10 million tons, and the average ash utilization ratio was 85% [8]. The amount of coal ash utilization has steadily increased while disposal has steadily decreased. Currently coal ash utilization is approximately doubled compared with that in the early 1990s, and the amount of coal ash disposal approximately reduced by half. However, the capacity of the landfill site is approaching its limit year by year. The promotion of coal ash utilization must be discussed seriously.

3.2. Characterization of Coal Ash

The different shapes of coal ash generally include spheres for that with a low fuse temperature point and irregular shapes for that with a high fuse temperature point. The average particle diameter of coal ash produced by combustion of pulverized coal is approximately 25 μm, coarser than clay and finer than granular sand, which is equal to silt in terms of soil quality. The main chemical components in coal ash are silica and aluminium oxide, which is close to pit soil (SiO_2: 60% - 70%, Al_2O_3: 10% - 25%). Fly ash produced by fluidized bed combustion has a higher CaO content than that produced by combustion of pulverized coal. Since the coal used in Japan is imported from different countries, its physical properties vary significantly. The chemical and physical properties of coal ash produced by combustion of pulverized coal are shown in **Table 1** and those resulting from fluidized bed combustion are shown in **Table 2**.

3.3. Utilization of Coal Ash in Various Fields

The utilization of coal ash in each sector is shown in **Figure 4**. The amount of coal ash used in the cement

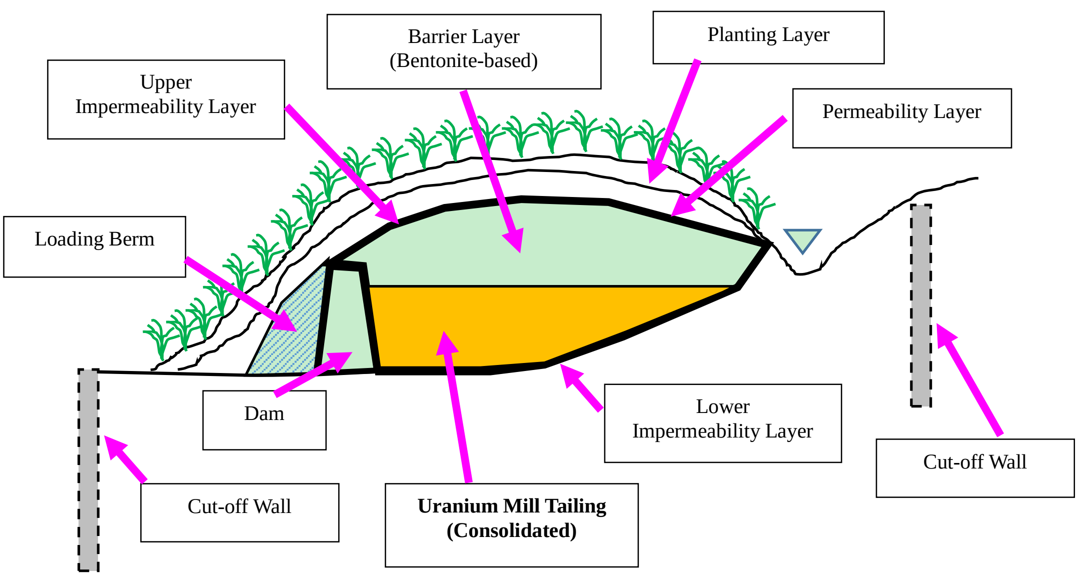


Figure 3. Schematic of dumping site in uranium mine.

Table 1. Main chemical and physical properties of pulverized coal combustion fly ash.

Properties			Number of samples	Maximum value	Minimum value	Average value
Chemical properties	Ignition loss	(wt%)	138	30.50	0.10	4.96
	SiO_2		138	76.90	44.50	58.76
	Al_2O_3		138	36.11	0.81	17.00
	Fe_2O_3		138	35.10	0.89	12.84
	CaO		138	11.70	0.0	3.58
	F-CaO		2	1.51	1.00	0.76
	MgO		138	2.97	0.08	1.05
	Na_2O		80	2.62	0.0	0.47
	K_2O		80	3.12	0.06	0.96
	SO_3		128	1.50	0.0	0.30
Physical properties	True specific gravity		128	2.47	1.92	2.20
	Bulk density (g/cm^3)	Dense	90	1.471	0.693	1.170
		Sparse	8	0.792	0.540	0.683
	Specific surface area (cm^2/g)	Blaine value	49	5720	1544	3212
		N2-BET	39	224,000	18,000	96,600
	Average grain diameter	µm	131	69.2	4.6	24.3

Table 2. Main chemical and physical properties of fluidized coal combustion fly ash.

Properties			Number of samples	Maximum value	Minimum value	Average value
Chemical properties	Ignition loss	(wt%)	13	32.3	5.9	18.4
	SiO_2		13	53.3	21.6	34.5
	Al_2O_3		13	25.7	8.3	17.4
	Fe_2O_3		13	4.8	0.4	2.1
	CaO		13	41.3	6.3	18.7
Physical properties	True specific gravity		12	2.61	2.26	2.48
	Specific surface area (cm^2/g)	Blaine value	10	9140	4210	6260

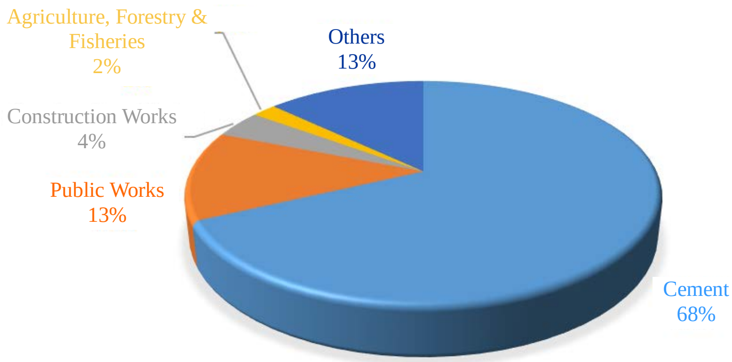


Figure 4. Coalash utilization by sector in Japan (2007) [9].

industry, which is one of Japan's major areas of utilization, accounts for 75% of the total, of which nearly 6.0 million tons of ash was used in the raw material for cement manufacturing. Limestone, clay and iron oxide are used as raw materials for cement, among which clay generally accounts for 15% of the total. The use of coal ash as a substitute for clay accounts for a large part of the current utilization of coal ash.

Although coal ash utilization for cement has rapidly increased since the late 1990s, its use in the manufactures of cement shows a leveling-off or decreasing trend recently. Due to decreasing the public works, it is difficult to expect an increase in use in this area in the future. Therefore, to deal with further increases in coal ash production, it is important to expand its utilization in other areas. Coal ash is particularly expected to be used as a material for cement/concrete admixtures or in public works where there is a high potential for large-scale utilization. **Table 3** lists coal ash utilization in each sector in FY2007.

The percentage of coal ash utilization in public works was approximately 10%. In this sector, coal ash has been mainly used as a road base material, for ground improvement. To expand the use of coal ash in this area, various technologies have been developed.

The rate of utilization in construction is approximately 5%. In this sector, coal ash has been used as a raw material for building boards and concrete products.

The rate of utilization in the agriculture, forestry and fisheries sector is approximately 2%. In this area, coal ash has been used for potassium silicate fertilizer and soil improvement material, which enjoys a small but steady demand.

3.4. More Utilization of Coal Ash

New applications of coal ash utilization in large volume must be developed. In addition, a contribution to the formation of a recycling-oriented society and to the development of coal ash utilization technology is expected when value is added to coal ash as marketable products. Coal ash as a cement raw material still remains the major application due to the size and stability of the cement market. However, the cement industry's capacity for raw material has almost reached its limit and the cost of coal ash to cement manufacturers is on the increase. Thus, other applications for coal ash utilization that are relatively more economical and diffusible are needed. From this perspective, institutions concerned have focused on developing various coal ash technologies based on hardened materials for public works, such as for ground improvement, revetment backfill and roadbed materials, and civil engineering uses, such as artificial aggregate or other materials to promote the use of large amounts of coal ash as a primary raw material. In addition, research is being conducted on the technology of retracting unburned carbon from coal ash for increasing the quality and stability and/or the technology of producing artificial zeolite characterized as having hydrophilicity and ionic exchangeability, etc., for application in water-retaining asphalt, purifying water, soil conditioners and many other new marketable applications.

A new application of coal ash as a substitute for bentonite that is considered as a barrier of nuclear waste disposal, was investigated by means of the laboratory testing in this research.

4. Required Properties of Bentonite Barrier Layer [7]

The extent and orientation of research into bentonites is given by the unique requirements set by the area of its

Table 3. Patterns of mixtures contents for specimens.

No.	Bentonite (wt%)	Fly Ash (wt%)	Water Content (%)
① Bentonite Only	100	0	5
② Bentonite + Fly Ash (Raw)	80	20	5
③ Bentonite + Fly Ash (Raw)	70	30	5
④ Bentonite + Fly Ash (Raw)	60	40	5
⑤ Bentonite + Fly Ash (Crushing)	80	20	5
⑥ Bentonite + Fly Ash (Crushing)	70	30	5
⑦ Bentonite + Fly Ash (Crushing)	60	40	5

exploitation. Bentonite, or a bentonite-based material, will be used as the main composition of an engineered barrier in the underground repository, preventing any potential leakage of radio nuclides from the container with high-level radioactive waste into a natural barrier and further into the biosphere. The engineered barrier must retain this capability for a period of up to hundreds of thousands of years. Within the engineered barrier, bentonite-based mixture will fulfil absorbing, filling and sealing functions. Therefore, among the basic geotechnical requirements for the bentonite-based barrier there are:

4.1. Impermeability (Filtration Coefficient k = 10^{-10} - 10^{-14} m/s)

The design of a bentonite-based material (mix), which will fulfil the required non-permeability parameters, does not represent the biggest problem. The material itself can fulfil this requirement without problems. The hazard of radio nuclide leakage, however, rapidly increases with the appearance of any discontinuity interface. Discontinuity interfaces are a potential source of formation of paths for the spread of dangerous radioactive substances in any state. Different types of interfaces may be distinguished, namely in relation to the way of their formation.

a) Discontinuity interfaces arising during preparation of multi-barrier system.
b) Discontinuity interfaces arising during multi-barrier system's construction.
c) Discontinuity interfaces arising during long-term operation of underground repository.

4.2. Swelling Capacity

Swelling capacity of the used material is important namely due to the necessity of sealing discontinuity interfaces and/or cracks in their contact with groundwater self-sealing. Swelling capacity, described in geotechnics by the value of swelling pressure, should be optimized by admixtures. Swelling pressure must not negatively affect the function of the container, the function of individual structural units of the engineered barrier or the function of the natural barrier.

4.3. Thermal Conductivity

The bentonite-based barrier material must be designed in such a way to facilitate easy removal of the heat radiated by the container further into the natural barrier. Thermal conductivity grows with the growing volume density and material moisture content. It also shows a slight increase with growing temperature. In order to facilitate heat removal from the container, bentonite mixture is treated by adding graphite. Groundwater leaking from the natural barrier into the engineered barrier gradually saturates part of it, which increases the thermal conductivity in the saturated medium. Thermal conductivity of the material within the barrier body will show changes in time.

4.4. Extremely Long-Term Unchangeability of Bentonite-Based Barrier's Behaviour

This requirement forms the most difficult part of research objectives. It is, however, evident, that implementation of this research requires a multi-disciplinary approach with the use of all available methods. Such methods include namely experimental research, physical and mathematical modelling and a study into natural analogues. Input parameters for mathematical models may be obtained namely by using laboratory testing, on-site tests and field measurements, research in underground laboratories. In this respect it should be mentioned that the accuracy of obtained results requires a practice in which the tests and experiments are carried out under the conditions corresponding to actual conditions. This means, for example, that strength tests of prefabricates should be performed at temperatures of 70˚C - 140˚C, the material should be subjected to long-term loading with this temperature before testing, or the thermal conductivity coefficient should be measured at this temperature and on a material saturated with water of a specific chemical composition under the conditions when it cannot change its volume, etc.

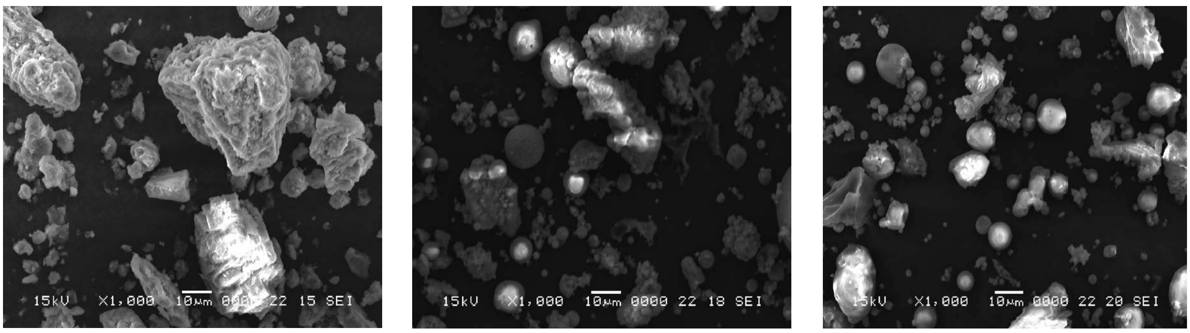
5. Laboratory Tests

This research investigates how much impact of different substitute ratio of fly ash for bentonite on the characteristics of bentonite-based barrier layer/buffer in order to discuss the applicability of fly ash as the content of bentonite-based barrier layer/buffer for radioactive waste disposal. A series of laboratory tests were conducted as follows.

5.1. Strength Test

In the case high-level radioactive waste disposal, the depth of is more than 300 m deep from the surface. At least, 8.1 MPa in vertical direction and 6.5 MPa in horizontal direction stresses are affected as the ground pressure. Even though several kinds of support systems are installed or measures such as a grouting are conducted, the strength of bentonite-based mixtures itself has to be in some extents. Therefore, the strength test under different fly ash-bentonite contents has been conducted in order to evaluate the applicability of fly ash and investigate the appropriate mix content for applying barrier layer/buffer for radioactive waste disposal.

The specimens were made with bentonite, fly ash, and water. Two different sizes of fly ash were employed (see **Figure 5**). Averages of the particle sizes of fly ash (raw) and fly ash (crushed) were 20 µm and 15 µm, respectively. Before molding, all contents were dried and water was sprayed on them and then they were left for 36 hours. A cylindrical mold 50 mm in diameter and 100 mm in length was used for specimens. Mixtures which volume is 1/3 of total volume of mold are put into in mold and then was pounded by falling heavy weight by twenty times. This procedure is repeated three times. After that, the specimens were removed from molds and shapes of both sides were restored. **Figure 6** shows the specimens for this test. Uniaxial compressive test and needle penetration test were performed for each specimen. **Table 3** shows the pattern of mixtures contents for specimens.



(a) (b) (c)

Figure 5. SEM images of bentonite, fly ash (raw) and (crushed). (a) Bentonite; (b) Fly ash (raw); (c) Fly ash (crushed).

Figure 6. Specimens for uniaxial compressive test.

Figure 7 shows the uniaxial compressive strengths under different mixture contents. It can be seen that the substitution of fly ash for bentonite improve the strength of bentonite-based mixtures and the strength of bentonite-fly ash mixtures increases with increasing its substitution ratio. The strength of bentonite-fly ash mixtures are from 0.8 MPa to 2.2 MPa and this range is almost the same as the soil around 300 m deep from the surface and meets the required properties. Moreover, depending on the site conditions, the strength of bentonite-based mixtures can be controlled as the required level by substituting fly ash for bentonite. In additions, as the particle size/distribution of fly ash has no obvious impact on the mechanical properties especially UCS of bentonite-fly ash mixtures, it can also be said that the original fly ash can be used and cost can be saved.

5.2. Falling Head Permeability Test

The characteristics of permeability of bentonite-fly ash mixtures is also one of the important key for barrier-layer/buffer for radioactive waste disposal in order to prevent immersed water to overpack from surrounding soil/groundwater and leak the radioactive materials from its inside. The falling head permeability test was conducted. **Figure 8** shows the equipment of falling head permeability test. Based on the results of strength tests, two different contents of bentonite-fly ash mixtures were selected and tested. **Table 4** shows the results of this

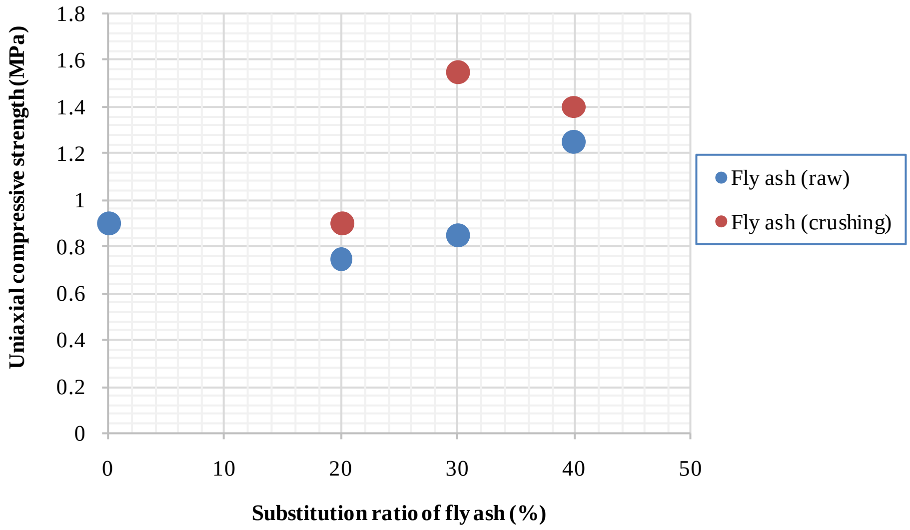


Figure 7. Uniaxial compressive strengths under different mixture contents.

Figure 8. Device of falling head permeability test.

permeability test. It can be said from this table that the permeability of bentonite-fly ash mixtures increases with increasing the substitution ratio of fly ash for bentonite. In other words, its barrier/sealing function decreases with increasing the substitution ratio of fly ash for bentonite. However, even if the substitution ratio of fly ash for bentonite is 50%, the permeability of bentonite-fly ash mixtures is still around 1.0×10^{-8} m/sec and this value can be considered as impermeable in practically from the engineering point of view. Moreover, it can be expected that the permeability of bentonito-fly ash mixture at 300 deep from the surface is lower than the value obtained from this test due to the consolidation of bentonite-fly ash mixtures by large ground pressure. Hence, it can be expected that the bentonite-based mixture meets the required impermeability even though a bentonite is substituted with fly ash in some extents.

5.3. Swelling Test

As mentioned above, swelling capacity is important due to the necessity of sealing discontinuity interfaces and/or cracks in their contact with groundwater self-sealing. Here, swelling capacity described by the value of swelling volume. **Figure 9** shows the equipment of swelling test. **Table 5** shows the results of swelling test. It can be said from this table that the swelling volume decreases with increasing substitution ratio of fly ash for bentonite. Moreover, the particle size of fly ash has no impact on the swelling characteristics of bentonite-fly ash mixtures. This is because only bentonite has swelling characteristics and fly ash does not have. Hence, it can be said that the barrier layer/buffer material has to contain bentonite in some extent in order to have the swelling capacity.

5.4. pH Value and Electro Conductivity Measurement

In the case of high-level radioactive waste disposal, bentonite-fly ash buffer contacts directly with the canisters and surrounding rock, not only its sealing characteristics of radioactive waste materials but also the impact/effect of buffer itself on surrounding rock/environment has to be investigated. For example, the chemical

Table 4. Results of permeability test.

No.	Permeability k_{15}
① Bentonite Only	7.4×10^{-8}
② Bentonite: Fly Ash (Raw) = 1: 1	2.0×10^{-6}
③ Bentonite: Fly Ash (Crushing) = 1: 1	1.0×10^{-6}

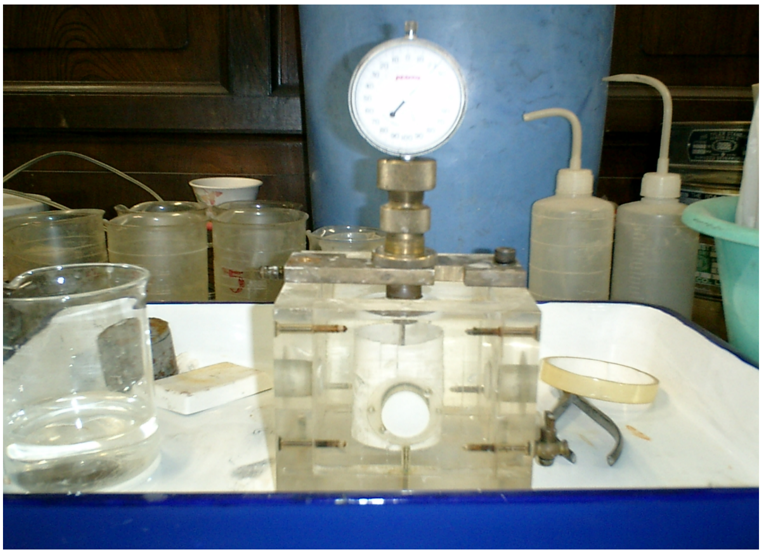


Figure 9. Device of swelling test.

reaction between buffer and surrounding rock and the leakage of contaminated material through the buffer by underground water flow, etc. Hence, pH value and electro-conductivity of bentonite-fly ash mixtures were measured under different substitution ratio of fly ash for bentonite.

Test procedures are as follows: the 100 ml of distilled water and 2.0 g of each sample put into a beaker. Then the top clear layer liquid was sampled and a couple of drop was put on the both sensors of pH and electro conductivity. **Table 6** shows the composition of test specimens.

Figure 10 and **Figure 11** show the relationship between the pH value/electro conductivity and elapsed time, respectively. The suspension of bentonite itself is classified as weak alkaline and the pH value of that of fly ash is 12 - 13 and this is classified as alkaline. Compared with these results, no obvious change of pH value and electro-conductivity due to the chemical reaction among bentonite, fly ash and water was observed under different composition ratios. However, as all of these samples represents alkaline, if underground flow has any impact of storage area, the application of neutralizer or other measures should be considered in order to restrain the impact of alkaline on the surrounding environment.

Table 5. Results of swelling test.

Specimen	Original Height [mm]	Vertical Displacement [mm]	Swelling Ratio [%]
Bentonite Only	36	5.64	15.7
Bentonite: Fly Ash (Raw) = 1: 1	46	4.63	10.1
Bentonite: Fly Ash (Crushing) = 1: 1	37.5	3.88	10.3
Bentonite: Fly Ash (Raw) = 1: 2	39	3.93	10.1
Bentonite: Fly Ash (Raw) = 1: 5	40	4.21	10.5
Bentonite: Fly Ash (Crushing) = 1: 5	38	4.02	10.6

Table 6. Compositions of test specimens.

Specimen No.	Compositions	Weight
①	Bentonite Only	2 g
②	Fly Ash (Raw)	2 g
③	Fly Ash (Crushing)	2 g
④	Bentonite: Fly Ash (Raw) = 1:1	1 g, 1 g
⑤	Bentonite: Fly Ash (Crushing) = 1:1	1 g, 1 g

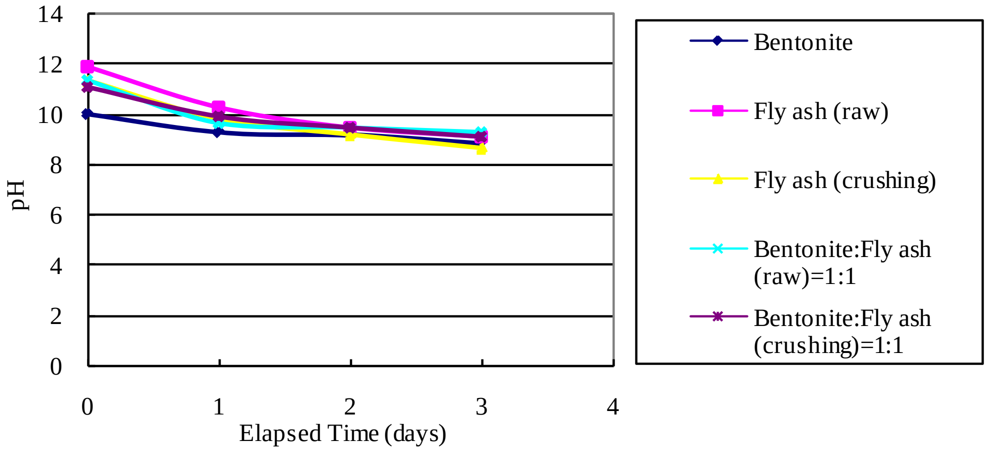


Figure 10. Relationship between pH value and elapsed time.

5.5. Thermal Conductivity Test

After the radioactive waste materials are stored, they generate heat and then the temperature of its inside rises gradually. Under these situations, the deterioration of buffer can be expected due to high temperature. In order to prevent this deterioration, the thermal conductivity of bentonite-fly ash mixtures has to be investigated. Low thermal conductivity prevents the diffusion of heat generated by radioactive waste materials to outside effectively and as a result the characteristics of buffer such as impermeability, thermal transfer, radionuclide transport, stress relaxation may be weaken due to the high temperature. Hence, the thermal conductivity is also one of the important characteristics of buffer material. In this research, a thermal conductivity of each specimen was measured by using the thermal conductivity meter QTM-500 (see **Figure 12**) and the impact of the different composition of fly ash-bentonite on the thermal conductivity was discussed. **Table 7** shows the compositions of test specimens.

Figure 13 shows the results of this test. It can be seen that the thermal conductivity increases with increasing substitution ratio of fly ash for bentonite. Moreover, the range of thermal conductivity is 0.3 - 1.5 W/mK. All of these values meet a required conditions proposed as the buffer for high-level radioactive waste. Hence, the substitution of fly ash for bentonite improves the thermal conductivity of barrier layer/buffer. However, in this test, the impact of rising temperature due to the heat generated by radioactive wastes on the thermal conductivity of bentonite-fly ash mixtures was not taken into account. The effect of high temperatures and elapsed long time should be investigated in the next.

6. Conclusion

The applicability of fly ash to the contents of barrier layer/buffer for radioactive wastes was investigated in this

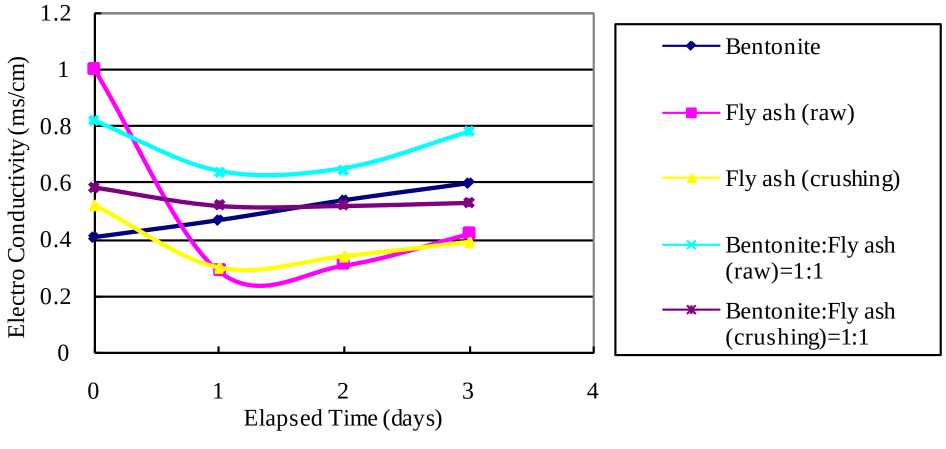
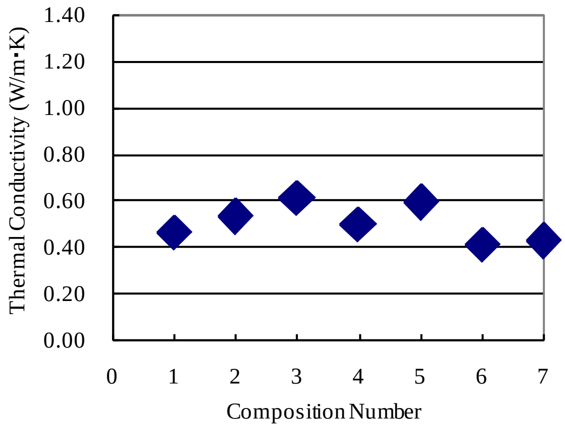


Figure 11. Relationship between electro conductivity and elapsed time.

Figure 12. Thermal conductivity meter QTM-500.

Table 7. Compositions of test specimens.

Specimen No.	Bentonite (wt%)	Fly Ash (wt%)	Water Contents (%)
① Bentonite Only	100	0	5
② Bentonite + Flyash (Raw)	80	20	5
③ Bentonite + Flyash (Raw)	70	30	5
④ Bentonite + Flyash (Raw)	60	40	5
⑤ Bentonite + Flyash (Crushing)	80	20	5
⑥ Bentonite + Flyash (Crushing)	70	30	5
⑦ Bentonite + Flyash (Crushing)	60	40	5



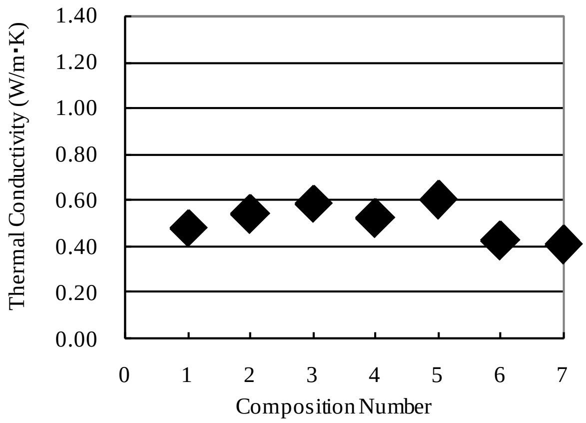


Figure 13. Thermal conductivity for each sample. (a) 3 days later; (b) 10 days later.

research. From the results of a series of laboratory tests, it can be recognized that the mechanical properties, permeability, thermal conductivity and sealing effect of the bentonite-fly ash mixtures meet the requirements for the buffer materials for radioactive waste disposal. Hence, it can be concluded that fly ash has a potential for use in them as the bentonite is substituted. However, in order to prove the ability and estimate the appropriate mixture contents, more research has to be conducted, such as colloid filtration effect and long-term stability/unchangeability.

Acknowledgements

This work was supported by JSPS KAKENHI Grant Number 21760679.

References

[1] Sustainable Japan (2015) (In Japanese). http://sustainablejapan.jp/2015/03/03/world-electricity-production/14138

[2] United States Nuclear Regulatory Commission (2010). http://www.nrc.gov/

[3] Berlin, R.E. and Stanton, C.C. (1989) Radioactive Waste Management. A Wiley-Interscience Publication, 444.

[4] Byalko, A.V. (1994) Nuclear Waste Disposal: Geophysical Safety. CRC Press, Boca Raton, 281.

[5] Nuclear Waste Management Organization of Japan (2010). http://www.numo.or.jp/

[6] Brookins, D.G. (1984) Geotechnical Aspects of Radioactive Waste Disposal. Springer-Verlag, New York, 321.

[7] Centre of Experimental Geotechnics (CEG) On the Faculty of Civil Engineering CTU (2010). http://ceg.fsv.cvut.cz/research/

[8] Yoshida, Y., Shimada, H., Sasaoka, T., Matsui, K., Nakagawa, H., Sakai, Y. and Gottfried, J. (2009) Consumption of Coal and Utilization of Coal Ash in Japan. *Proceedings of* 13*th Conference on Environment and Mineral Processing*, **1**, 291-301.

[9] Japan Coal Ash Association (2007) (In Japanese). http://www.japan-flyash.com/pdf/fcuse10.pdf