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Safety Assessment for the Landfill Disposal of Decommissioning Waste Solidified by Magnesium Potassium Phosphate Cement

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The decommissioning of a nuclear power plant generates large amounts of radioactive waste, which is of several types. Radioactive concrete powder is classified as low-level waste, which can be disposed of in a landfill. However, its safe disposal in a landfill requires that it be immobilized by solidification using cement. Herein, a safety assessment on the disposal of solidified radioactive concrete powder waste in a conceptual landfill site is performed using RESRAD. Furthermore, sensitivity analyses of certain selected input parameters are conducted to investigate their impact on exposure doses. The exposure doses are estimated, and the relative impact of each pathway on them during the disposal of this waste is assessed. The results of this study can be used to obtain information for designing a landfill site for the safe disposal of low-level radioactive waste generated from the decommissioning of a nuclear power plant.

Keywords: Decommissioning waste, Solidified waste, Landfill disposal, Safety assessment, Exposure dose

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1. Introduction

The safe management of decommissioning waste is emerging issue, especially after the decision to shut down the Kori 1 nuclear power plant (NPP) in Korea permanently in 2017 [1]. During the decommissioning of an NPP, various types and large amounts of radioactive waste with different characteristics compared to the operational waste are generated during the relatively short period. Therefore, a safe management policy including the treatment and disposal of decommissioning waste should be established. The typical forms of radioactive waste generated from the decommissioning of a PWR nuclear power plant are summarized in Table 1 [2]. For the safe and efficient management of decommissioning waste, its volume can be reduced by the decontamination and reuse of steel waste. In addition, several other types of decommissioning waste can be solidified with concrete or a polymer to ensure mechanical stability and a low release rate of radionuclides.

Most decommissioning waste can be classified as a low-level waste (LLW) and very low-level waste (VLLW) according to the concentration of radioactivity. Low-level decommissioning waste can be disposed of in a near-surface disposal facility and very low-level decommissioning waste can be disposed of in landfill sites according to regulations pertaining to the classification of the radioactive waste and regulatory clearance laws in Korea [3]. For the safe and reliable disposal of these types of waste, safety assessments are conducted using an appropriate computer program.

For the safety assessment of a landfill disposal site for radioactive waste, we utilize concrete powder waste generated from the decommissioning an NPP as a typical form of very low-level decommissioning waste. This type can be solidified with cement or a polymer to ensure both mechanical stability and a low release rate of radionuclides, as noted above. A recent research program suggested the use of magnesium potassium phosphate cement (MKPC) to solidify this type of concrete powder waste [4]. Through several tests, it was demonstrated that the concrete

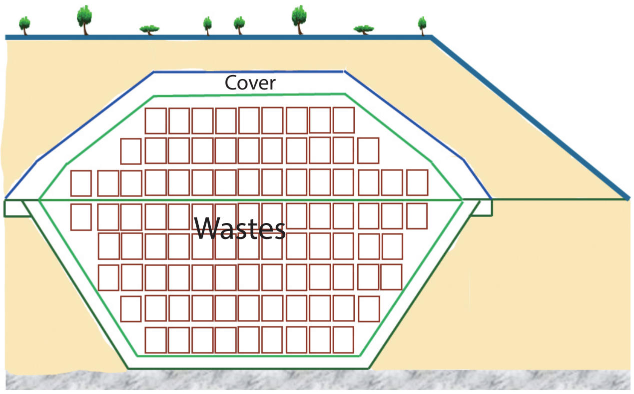

Fig. 1. A schematic view of a typical trench for a landfill site.

Table 1. Typical radioactive waste types during the decommissioning of a PWR nuclear power plant [2]

Radioactive material generation	Radioactive Waste (ton)	Percentage (%)
Activated steel	650	10.5
Activated concrete	300	4.9
Contaminated ferritic steel	2,400	38.7
Steel likely to be contaminated	1,100	17.7
Contaminated concrete	600	9.7
Contaminated lagging	150	2.4
Contaminated technological wastes	1,000	16.1
Total	6,200	100

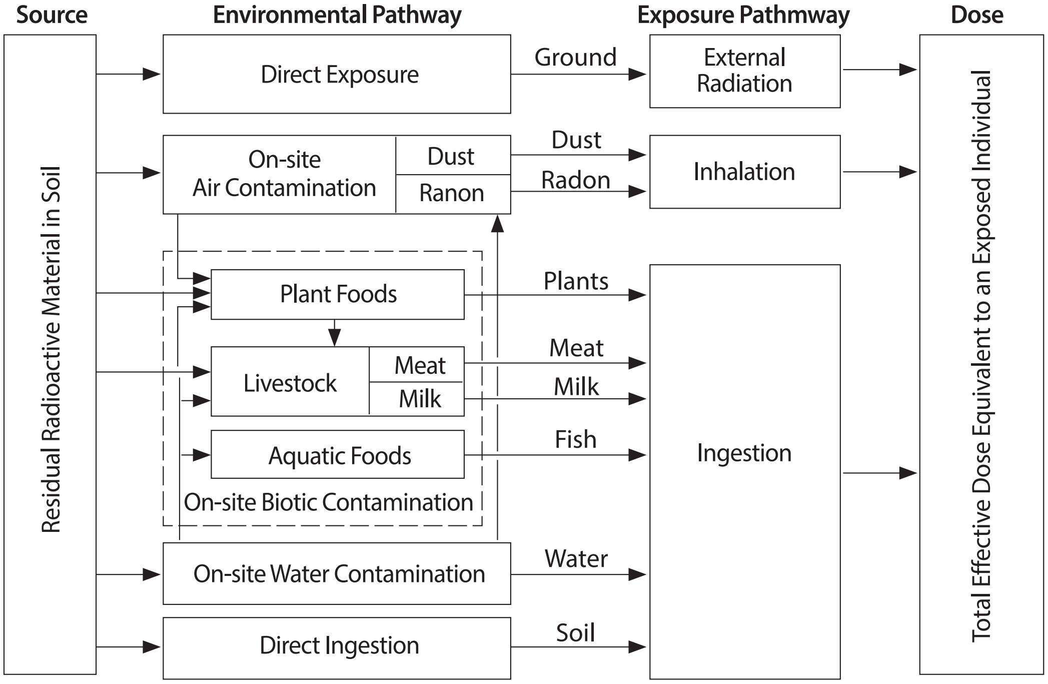

Fig. 2. Exposure pathways considered in the RESRAD-ONSITE code [7].

powder waste solidified with MKPC can be used to immobilize radioactive concrete waste. The results also demonstrated that MKPC specimens satisfy waste acceptance criteria, specifically the compressive strength and leachability index.

In this study, we estimated exposure doses for the disposal of concrete powder waste solidified with MKPC in a landfill site to assess the feasibility of this disposal method in terms of radiological safety. We use RESRAD-ONSITE Ver. 7.2 to estimate the exposure doses resulting from the disposal of this type of waste in a conceptual design of a landfill site [3]. A typical conceptual design of a landfill site for the disposal of VLLW consists of trench-type disposal facilities and a cover, as shown in Fig. 1 [5]. Trench-type disposal facilities are necessary to retard the migration of radionuclides through the groundwater in the event of a release of radionuclides. The function of the cover is to restrict precipitation, which may penetrate into disposal facilities. We also conducted sensitivity analyses of important input variables to investigate their effects on the exposure dose. The results of this study can be used to obtain useful insight into the detailed design of a landfill site for the disposal of very low-level radioactive waste.

2. Materials and Methods

2.1 Solidified Concrete Waste

As shown in Table 1, contaminated concrete among the decommissioning waste is generated as a result of neutron activation during the operation of an NPP. A recent research suggested the solidification of cement paste powder wastes with cement [4]. They suggested MKPCs as a solidification material for the immobilization of radioactive cement powder waste, as MKPCs have high early strength, high bonding strength, slight drying shrinkage, low permeability, and high sulfate resistance. In that study, 50wt% of

Table 2. Important input data for the estimation of exposure doses

Parameter	Unit	Value
Area of contaminated zone	m^2	14,250
Thickness of contaminated zone	m	16
Length parallel to aquifer flow	m	600
Depth of cover	m	0.5
Density of cover material, saturated zone and unsaturated zone	$g\cdot cm^{-3}$	1.6
Erosion of contaminated zone	$m\cdot yr^{-1}$	0.001
Total porosity of contaminated zone	-	0.15
Effective porosity of saturated zone and unsaturated zone	-	0.2
Hydraulic conductivity of contaminated zone and unsaturated zone	$m\cdot yr^{-1}$	10
Hydraulic conductivity of saturated zone	$m\cdot yr^{-1}$	100
Thickness of unsaturated zone	m	4
Hydraulic gradient of saturated zone	-	0.02
Evapotranspiration coefficient	-	0.68
Water table drop rate	$m\cdot yr^{-1}$	0.001
Well pumping rate	$m^3\cdot yr^{-1}$	250
Wind speed	$m\cdot sec^{-1}$	2.1
Precipitation	$m\cdot yr^{-1}$	1.7
Runoff coefficient	-	0.2
Watershed area for nearby stream or pond	m^2	1,000,000
Humidity in air	$g\cdot m^{-3}$	8.0
Inhalation rate	$m^3\cdot yr^{-1}$	8,400
Exposure duration	yr	30
Indoor time fraction	-	0.5
Outdoor time fraction	-	0.25

simulated concrete powder waste (SCPW) was prepared and then mixed with MKPCs.

A solidified waste specimen was then created by adding contaminants such as Co and Cs ions to the mixture of the simulated concrete powder waste and MKPCs. With these MKPC specimens, they conducted several tests to determine the composition data and particle size distribution and to check the waste acceptance criteria such as the compressive strength and the leachability index [4]. In the present study, we subject this type of concrete powder waste specimen, disposable into a landfill site, to a safety assessment. The size of the solidified waste specimen is as follows: a diameter of 1.3 cm, a height of 2.6 cm, and a density of 2.532 $g\cdot cm^{-3}$ [4].

2.2 RESRAD-ONSITE Code

The estimation of the exposure doses was conducted with the RESRAD-ONSITE Ver. 7.2 code developed by the Argonne National Laboratory [6-7]. It is widely used to assist in developing cleanup criteria and assessing the dose or risk associated with radioactive materials in several countries. The exposure pathways used in the RESRAD-ONSITE code are direct exposure to external radiation from contaminated soil material and internal doses from the inhalation of airborne radionuclides. In addition, the ingestion of plant foods, meat, milk, drinking water, fish, and contaminated soil is also considered. All these significant exposure pathways are shown in Fig. 2.

2.3 Input Variables and Scenarios

To estimate the exposure doses resulting from the landfill disposal of solidified concrete waste, we assumed that all of the disposal areas are filled with this type waste. In addition, we assumed that the solidified concrete waste with MKPCs has no barrier credit. This means that all disposal areas are contaminated with the radioactivity contained in the solidified waste specimen. There are no radioactivity concentrations in solidified concrete waste with MKPCs because stable isotopes of Co and Cs are added during the manufacturing process. However, we assumed the radioactivity of Co and Cs in the solidified waste specimen to be one tenth of the upper threshold radioactivity value in each case, allowing classification as very low-level radioactive waste [4]. In addition, we assumed that the radionuclides of Co and Cs are ^{60}Co and ^{137}Cs, respectively. Therefore, we use 1.0 Bq·g^{-1} for the radioactivity concentration for both ^{60}Co and ^{137}Cs.

Most of the input data for the primary contamination zone and the cover are derived from references for the conceptual design of a landfill site [5, 8, 9, 10]. According to these reports, the cover consists of multiple layers of soil, sand, a membrane, and gravel with different depths and different characteristics, such as the density and erosion rate. We used the average values of the density and erosion rate of the cover material here because we could not consider multiple layers of the cover when using the RESRAD-ONSITE code. The important input data for the estimation of exposure doses are summarized in Table 2. In addition, input data for the ingestion pathway are summarized in Table 3 [10]. We also conducted sensitivity analyses of certain input parameters of the cover materials to investigate their effects on the exposure dose.

Table 3. Input data for the ingestion pathway [10]

Scenario	Consumption values
Fruit, vegetable, and grain	190 kg·yr^{-1}
Leafy vegetable	100 kg·yr^{-1}
Milk	63 L·yr^{-1}
Meat and poultry	55 kg·yr^{-1}
Fish	79.3 kg·yr^{-1}
Other seafood	33.4 kg·yr^{-1}
Drinking water intake	196.3 L·yr^{-1}

There are many potential exposure scenarios such as the resident farmer and the industrial worker. Exposure scenarios are defined as patterns of human activity that can affect the release of radioactivity from the contaminated zone and the amount of the exposure dose received at the exposure location. In the RESRAD-ONSITE code, a resident farmer scenario, a suburban resident scenario, an industrial worker, and a recreationist scenario are considered for the estimation of the exposure doses. For each scenario, different pathways and different values of input parameters are considered for the estimation of the exposure dose [7]. In this study, we considered a resident farmer scenario and an industrial worker scenario for the exposure dose estimations. The pathways and key parameters used for both the resident farmer and industrial worker scenarios are summarized in Tables 4 and 5, respectively.

Table 4. Pathways to be considered for the resident farmer and the industrial worker scenarios

Pathway	Scenario	
	Resident farmer	Industrial worker
External gamma exposure	Yes	Yes
Inhalation of dust	Yes	Yes
Radon inhalation	Yes	Yes
Ingestion of plant foods	Yes	No
Ingestion of meat	Yes	No
Ingestion of milk	Yes	No
Ingestion of fish	Yes	No
Ingestion of soil	Yes	Yes
Ingestion of water	Yes	No

Table 5. Key parameters used in the resident farmer and the industrial worker scenario

Parameter	Resident farmer	Industrial worker	Unit
Exposure duration	30	25	yr
Inhalation rate	8,400	11,400	$m^3 \cdot yr^{-1}$
Fraction of time indoors	0.50	0.17	-
Fraction of time outdoors	0.25	0.06	-
Contaminated fractions of food			
Plant food	0.5	0.1	-
Milk	1.0	Not used	-
Meat	1.0	Not used	-
Aquatic food	0.5	Not used	-
Soil ingestion	36.5	36.5	$g \cdot yr^{-1}$
Drinking water intake	510	Not used	

3. Results and Discussion

3.1 Estimation of Exposure Doses

The estimations of the exposure dose for the disposal of solidified cement powder waste with MKPCs were formulated using the basic input data summarized in Table 2. The exposure doses as a function of time are shown in Fig. 3. As shown in this figure, even at the time of disposal, the total exposure dose does not in any case exceed 0.1 $mSv \cdot yr^{-1}$, which is the safety goal for the regulation of the low-and intermediate-level radioactive waste repositories, despite our use of one tenth of the upper threshold value of the radioactivity concentration for ^{60}Co and ^{137}Cs. This means that the waste specimens considered in this study can be safely disposed of in a landfill. The exposure doses decrease with time and become negligible at the time of 100 years, which is the provisional institutional control period of a radioactive waste repository in Korea.

In Fig. 4, we plot the contributions of each of the exposure pathways to the total exposure at 30 years that is a provisional institutional control period of a landfill site. The most important pathway is that associated with the ingestion of plants for both ^{60}Co and ^{137}Cs, as plants above contaminated areas may be affected by these radionuclides directly. The second most import pathways are external exposure from the ground for ^{60}Co and the ingestion of meat for ^{137}Cs. This may be due to the different transport characteristics of these radionuclides resulting from the different sorption and dissolution behaviors. The contribution of the inhalation pathway does not appear due to the sufficient cover depth. This means that radionuclides are not released into the atmosphere if a sufficient cover depth is secured. We used 0.5 m as basic input data for the cover depth. According to simulation results with different cover depths, the exposure dose from the inhalation pathway does not occur if the cover depth exceeds 0.1 m. Therefore, we can disregard the exposure dose from the inhalation pathway if we secure a sufficient cover depth.

3.2 Exposure Doses for Scenarios

We estimate exposure doses for the industrial worker scenario considering the pathways and key parameter values summarized in Tables 4 and 5. The total exposure dose is approximately 1.0×10^{-4} $mSv \cdot yr^{-1}$, which is much lower

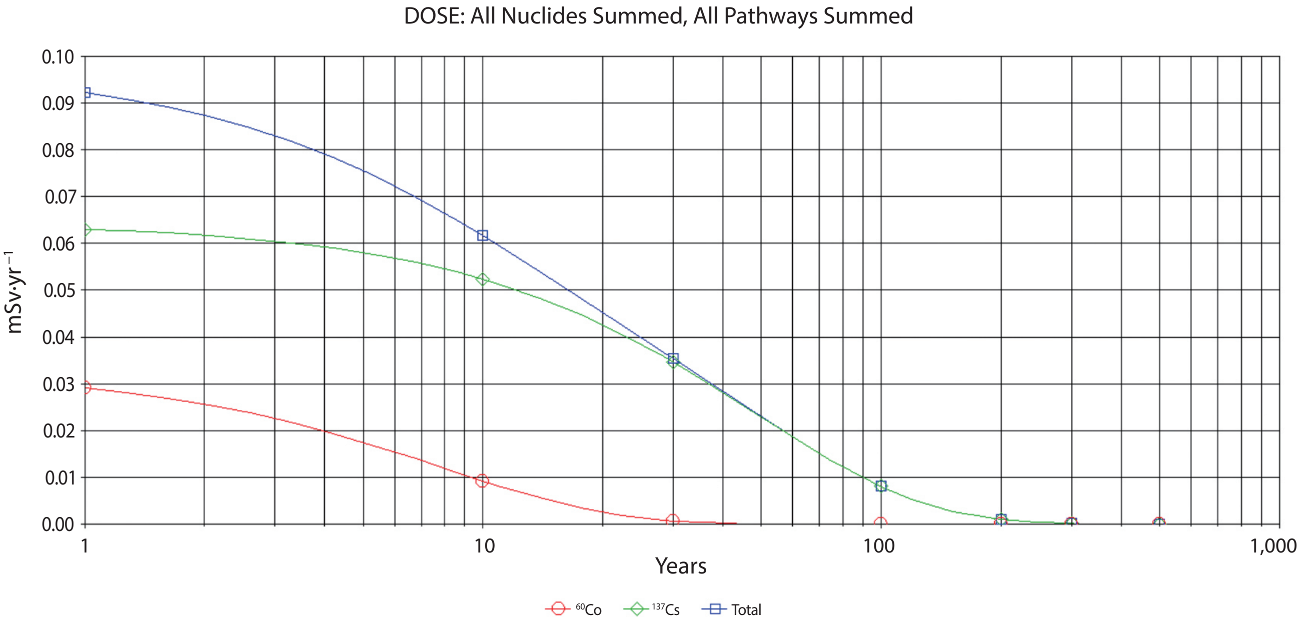

Fig. 3. Exposure doses as a function of time.

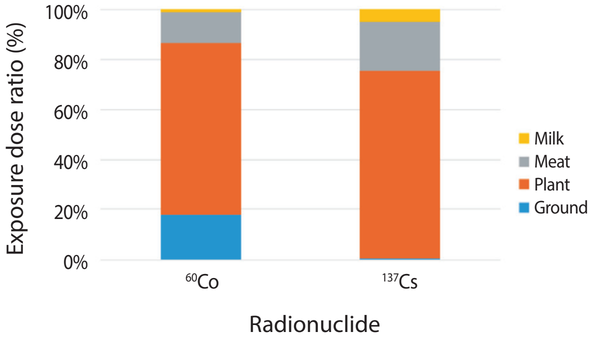

Fig. 4. Exposure dose ratio for each exposure pathway for each radionuclide at 30 years.

than the regulation criteria of the exposure dose for radiation workers. Moreover, only the exposure doses from external exposure from the ground and the ingestion of soil occur because the ingestion pathways are not considered in this scenario, as summarized in Table 4. The exposure dose from the inhalation pathway does not occur due to the sufficient cover depth of 0.5 m. To investigate the influence of the inhalation pathway on the total exposure dose, we re-estimate the exposure dose using 0.1 m as a cover depth. The total exposure dose is then estimated to be approximately 0.3 mSv·yr^{-1}, which is much greater than the exposure dose without the inhalation pathway. Therefore, appropriate measures must be taken to restrict the exposure dose from the inhalation pathway for the protection of industrial workers because this pathway is crucial for the exposure dose for industrial workers if a sufficient cover depth is not secured.

We estimate the exposure doses for the resident farmer scenario considering the pathways and key parameter values summarized in Tables 4 and 5. We used the internal dose coefficients derived from ICRP 72 to estimate the exposure doses in this case [11]. According to this report, age-dependent dose coefficients for infants and those age 1, age 5, age 10, age 15, and adults are given. Therefore, we estimate the exposure doses using these age-dependent dose coefficients. The total exposure doses are as follows: 0.065 mSv·yr^{-1} for infants, 0.015 mSv·yr^{-1} for those age 1, 0.029 mSv·yr^{-1} for those age 5, 0.029 mSv·yr^{-1} for those age 10, 0.036 mSv·yr^{-1} for those age 15, and 0.305 mSv·yr^{-1} for adults. The differences in the exposure doses here stem

Table 6. Exposure doses for different cover depths (mSv·yr^{-1}) at 30 years

Cover depth (m)	Pathway					Total
	Ground	Plant	Meat	Milk	Soil	
0.1	2.02×10^{-1}	5.12×10^{-2}	1.47×10^{-2}	3.55×10^{-3}	9.53×10^{-5}	2.71×10^{-1}
0.3	8.11×10^{-2}	3.88×10^{-2}	1.01×10^{-2}	2.38×10^{-3}	0	1.32×10^{-1}
0.5	3.28×10^{-2}	2.65×10^{-2}	6.87×10^{-3}	1.63×10^{-3}	0	6.78×10^{-2}
1.0	3.49×10^{-3}	0	0	0	0	3.49×10^{-3}
3.0	6.68×10^{-7}	0	0	0	0	6.68×10^{-7}

from the differences in the internal exposure doses because different dose coefficients for internal exposure pathways such as an inhalation and ingestion are used for the six age groups. Although there are very small differences among them, the maximum exposure doses occur for an infant.

3.3 Sensitivity Analyses of the Input Parameters of the Cover

The cover of a landfill site plays several very important roles, such as securing the mechanical stability of a landfill site, reducing internal exposure dose levels by restricting the release of radionuclides to the atmosphere, and restricting the inflow of precipitation into the disposal area for the mechanical protection of radioactive waste. In general, soil, sand, gravel, and membranes such HDPE (high-density polyethylene) are suggested as cover materials for landfill sites. In addition, multiple layers made of these materials with different depths can also serve as the cover of a landfill site. Therefore, there can be different values of characteristic data and depths of the cover of a landfill site. We selected the cover depth, erosion rate, and density of the cover material as the input parameters of the cover for the sensitivity analyses conducted here.

First, we estimated and analyzed the total exposure doses for different values of the cover depth of 0.1 m, 0.5 m, 1.0 m, and 3.0 m. The resulting exposure doses for each pathway at 30 years are summarized in Table 6. As shown in Table 6, the total exposure doses and the exposure doses for each pathway decrease as the cover depth increases. Specifically, the exposure dose for the ingestion of soil occurs only for the cover depth of 0.1 m, which means that there are no exposure doses from the ingestion of soil if the cover depth exceeds 0.1 m. Therefore, there can be no exposure dose from the ingestion of soil if we secure a sufficient cover depth. As the cover depth decreases, the important exposure pathway is the external exposure from the ground because radionuclides may be released to the ground surface due to a shallow cover depth. In addition, there is only external exposure from the ground surface if the cover depth exceeds 1.0 m. If we use 3.0 m as a cover depth, as suggested in the conceptual design of a landfill site, the total exposure doses from the disposal of solidified concrete powder waste with MKPC into a landfill site can be negligible.

Next, we estimated and analyzed the total exposure doses for different erosion rates of the cover material because different cover materials with different erosion rates can be used as a cover material. The variation of the exposure doses for each pathway at erosion rates of 0.0001 m·yr^{-1}, 0.001 m·yr^{-1}, and 0.01 m·yr^{-1} are summarized in Table 7. As shown in Table 7, the total exposure doses increase as the erosion rate of the cover material increases because radionuclides may be released to the ground surface due to the rapid erosion of the cover material. The exposure dose from the ingestion of soil occurs only at an erosion rate

Table 7. Exposure doses for different erosion rates of a cover material (mSv·yr^{-1}) at 30 years

Erosion Rate (m·yr^{-1})	Pathway					Total
	Ground	Plant	Meat	Milk	Soil	
0.0001	2.28×10^{-4}	2.48×10^{-2}	6.44×10^{-3}	1.52×10^{-3}	0	3.30×10^{-2}
0.001	3.34×10^{-4}	2.65×10^{-2}	6.87×10^{-3}	1.63×10^{-3}	0	3.54×10^{-2}
0.01	1.64×10^{-2}	4.34×10^{-2}	1.12×10^{-2}	2.66×10^{-3}	0	7.37×10^{-2}
0.1	2.84×10^{-1}	5.54×10^{-2}	1.70×10^{-2}	4.17×10^{-3}	1.64×10^{-2}	3.61×10^{-1}

of 0.1 m·yr^{-1} due to the rapid release of radionuclides to the ground surface. Moreover, there are no exposure doses from the ingestion of soil when the erosion rate is less than 0.1 m·yr^{-1}. As shown in Table 7, the total exposure dose exceeds 0.1 mSv·yr^{-1}, which is the safety goal for low-and intermediate-level radioactive waste repositories. Therefore, any cover material for which the erosion rate exceeds 0.1 m·yr^{-1} is not suitable for this purpose.

In addition, we estimated and analyzed the total exposure doses for different densities of the cover material of 0.5 g·cm^{-3}, 1.0 g·cm^{-3}, and 1.5 g·cm^{-3}. As the density of the cover material changed, only the external exposure dose from the ground surface changed. As the density of cover material increases, the external exposure dose from the ground surface decreases. Therefore, an increase in the density of the cover material may restrict the release of radionuclides to the ground surface; however, this may not affect the transport of radionuclides to foodstuffs.

4. Conclusions

To check the feasibility of disposing of solidified concrete powder waste with MKPCs in terms of radiological safety, we estimated exposure doses resulting from the disposal of this material into a landfill with the RESRAD-ONSITE code. The main input parameters were derived from references with regard to the conceptual design of a landfill site. We assumed that the radioactivity concentrations of ^{60}Co and ^{137}Cs, both at 1.0 Bq·g^{-1} and one tenth of the upper threshold radioactivity values in each case, can be classified as very low-level radioactive waste because solidified concrete powder waste with MKPC contains stable isotopes of ^{60}Co and ^{137}Cs. We found that total exposure doses are below 0.1 mSv·yr^{-1}, which is the safety goal for low-and intermediate-level radioactive waste repositories. In addition, the compressive strength of the specimens is above 45 MPa and leachability indices of Co and Cs are 17.63 and 11.45 according to the test results of the MKPC specimens [4]. It means that the compressive strength and the leachability indices of the MKPC specimens satisfy the waste acceptance criteria. Therefore, solidified concrete powder waste with MKPCs containing ^{60}Co and ^{137}Cs can be disposed of into a landfill safely. We also estimated exposure doses for resident farmer and industrial worker scenarios and found that they were also below 0.1 mSv·yr^{-1}. In addition, we conducted sensitivity analyses of the input parameters of the cover material, as the cover of a landfill site is a very important component to secure mechanical stability and to restrict the release of radionuclides into the environment. The results of these sensitivity analyses can provide useful insights regarding the detailed design of a landfill site for the disposal of very low-level decommissioning waste.

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