Experimental Study on the Engineering Characteristics of Mixed Buffer/Backfill Materials

JI Lei¹, WANG Chuan-le²*, HAN Yang³, YOU Ye-chao⁴, XU Guo-dong¹, GONG Hui¹

¹ Jiangsu Construction Quality Inspection Center Co., Ltd., Nanjing 210033, China;  
² School of Transportation, Southeast University, Nanjing, Jiangsu 211189, China  
³ Nanjing Urban Construction Management Group Co., Ltd., Nanjing, Jiangsu 210006, China  
⁴ JSTI Group Nanjing, Jiangsu 210006  
*Corresponding author: E-mail: wang_chuanle@126.com

Abstract: Previous studies on buffer/backfill materials have been primarily focused on certain performances, and studies on the comprehensive screening of the engineering characteristics of such materials are scarce, and to ensure the safe operation of disposal repositories, new materials are needed. Therefore, to obtain the optimal mix ratio that meets the requirements for the operation of disposal repositories, and on the basis of existing literature, the thermal conductivity, impermeability, and shear resistance of buffer/backfill materials with different mix ratios were comprehensively screened to determine the effect of different components on these abovementioned properties. The results obtained showed that the addition of starch could improve the compactness of the mixed buffer/backfill materials, increase the contact area between the particles in the material, and improve their thermal conductivity, impermeability, and shear resistance to varying degrees. The peak value of the permeability of the mixed material was attained when the sand mixing ratio was 20%. Moreover, an increase in the dry density, starch content, and graphite content resulted in an increase in the internal friction angle and cohesion force of the composite materials. As the sand mixing ratio increased, the internal friction angle of the material first increased, and then decreased as the sand mixing ratio was further increased. At the peak sand mixing ratio (~20%), a decrease in the cohesion force was observed. Based on these results and on the engineering requirements for buffer/backfill materials destined for application in disposal repositories, the optimal mix ratio was selected according to the principle of “pilot heat, re-impermeability, and post-strength,” and the recommended formula for hybrid buffer/backfill materials was obtained.

Keywords: high-level waste repository; GMZ bentonite; mixed cushioning backfill material;

1. Introduction
Deep geological disposal is an internationally recognized feasible disposal method for high-level waste [¹], and buffer/backfill materials, which act as the last artificial barrier of the geological disposal repositories for high-level waste [²], must have good thermal conductivity, compressibility, absorbability, stability, and expansibility properties [³-⁸]. To ensure the integrity and stability of engineering such barriers, Pusch (1979) proposed that buffer/backfill materials must be characterized...
by extremely low permeability, high cation exchange capacity, high mechanical strength, high thermal conductivity, and good mechanical properties [9]. Therefore, the study of buffer/backfill materials should be focused on the exploration of their thermal conductivities, impermeabilities, and shear strength characteristics. In this regard, experts and scholars in the industry have conducted several related studies and have reported several results.

Tang et al. investigated the effect of dry density, water content, and saturation on the thermal conductivity of MX80 bentonite [10]. Cui and Cui studied the thermodynamic parameters of MX80 bentonite in the United States, and reported a linear relationship between void gas volume and thermal conductivity [11]. Acovsky studied the thermal conductivity of RMN bentonite, and observed that its dry density and moisture content have significant effects on its thermal conductivity [12]. Guo-ping et al. measured and analyzed the thermal conductivity of Gaomiaozi bentonite. Based on their findings, they reported that the thermal conductivity of the specimen increased as its sand mixing ratio and water content increased [13]. To study the thermal conductivity of bentonite and quartz sand mix materials, Wei-min and Hong et al. used the thermal probe method. Additionally, using various heat conduction models, they predicted and compared the thermal conductivity of the mixed materials [14]. Wei-min and Yong-gui et al. observed that on the basis of maintaining a certain level of expansive force, adding quartz sand to bentonite could enhance the strength and thermal conductivity of the resulting mixed material. However, they also observed a slight decrease in the self-healing property and water-resistance ability of this mixed material [15]. Yue-miao (2001) et al. studied the thermal conductivity of quartz sand (GMZ 01) and a graphite mixed material (GMZM) under different water contents and different compaction densities. They observed that the thermal conductivity of the buffer/backfill material was correlated with its microstructure, dry density, water content, and mineral composition [16]. Ao-ni and Ji Lei et al. used the transient plane heat source method to test and analyze the thermal conductivity of bentonite with respect to different proportions of quartz sand, zeolite, and graphite under different moisture contents and different dry density conditions. Thus, they proposed the recommended mix ratio for the buffer/backfill material [17]. Yue-miao et al. found that, owing to the special property of bentonite with respect to water expansion as well as the influence of its constituent stagnant water film, there was a significant decrease in the permeability coefficient of the bentonite as the compaction dry density increased. Thus, the permeability coefficient of compacted bentonite was extremely low [18]. Sheng-fei et al. analyzed the relationship between permeability coefficient and time using the conventional variable head permeability test. Based on their results, they proposed a solution to reduce the test error [19]. Hu-yuan studied the engineering performance of a clay-bentonite mixture via indoor compaction tests, penetration tests, and direct shear tests [20]. Thereafter, based on the results of their study on the joint sealing and healing of a buffer/backfill material block, they proposed an optimal joint scheme [21]. Jian et al. studied the compaction performance of mixed materials under both dynamic and static compactions, summarized the influence mechanism of the sand mixing rate and compaction energy on the compaction effect, and analyzed the relationship between the maximum dry density and the optimal water content [22]. Ling-yan introduced the concepts of effective moisture content and effective clay density via testing and analysis, and analyzed the shear strength indexes of samples under the optimal moisture content based on different standards [23]. Ping et al. added different proportions of starch to bentonite for molding treatment, and found that the bentonite strength was optimal when the starch content was 1.15% [24]. Additionally, Dean et al. studied the influence of standing time on the strength of high Miaozi sodium bentonite under different water contents [25].

However, most previous studies on buffer/backfill materials have been focused on one of the above characteristics, and so far, a comprehensive evaluation and screening of these engineering characteristics has not yet been performed. Additionally, there is still room for exploration in the research and development of new materials. Therefore, in this study, in view of this research status, the thermal conductivity, permeability, and shear strength of the proposed mixed material buffer/backfill material were investigated, and the effects of the content of each component on the three engineering properties were also investigated. Accordingly, coupled with the actual engineering requirements of buffer/backfill materials for application in high-level waste disposal repository, and in accordance with
the "pilot heat, re-impermeability, and post-strength" principle, the optimal mix ratio was obtained as the recommended formula for mixed buffer/backfill materials.

2. Material
Sodium bentonite with excellent thermal conductivity was selected as the base material for this study. Owing to its good thermal conductivity, stable physical and chemical properties, as well as its unique skeleton efficiency, quartz sand was used. Additionally, graphite was used given its high thermal conductivity, resistance to high temperatures, as well as its good adsorption property, and zeolite was used owing to its excellent adsorption property, ion exchange property, catalytic effect, acid resistance and heat resistance. Starch, which is commonly used as a binder in the preparation of mixed materials was used given that it helps to improve the compactness of the blended material. Additionally, it has been reported that a starch content of 1.15% enhances the engineering characteristics of mixed backfill materials, and results in an optimal bentonite intensity. For the purpose of the tests, quartz, ordinary graphite crushed to particle sizes of 2000 µm, commercial purpose natural zeolite crushed to particle sizes of 200 µm, and starch, which served as the main admixture, were chosen. To simulate the engineering environment of the actual operation of the high-level waste disposal repository to the greatest extent, deep groundwater from Beishan was collected from the Beishan Pit exploration site for water tests. The SEM images of the raw materials are shown in Fig. 1. Moreover, the basic physical and chemical properties of the raw material are shown in Table 1, and the chemical composition of the deep groundwater in Beishan is shown in Table 2.

![Photo and SEM image of the sodium-based soil powder (N).](image1)

![Photo and SEM image of quartz sand (S).](image2)

![Photo and SEM image of graphite (M).](image3)

![Photo and SEM image of zeolite (F).](image4)

![Photo of starch (D).](image5)

![Beishan groundwater.](image6)

Figure 1. Photos and micrographs of raw materials

| Raw material          | Proportion / (g/cm³) | Maximum particle size /mm | Color       | Primary minerals                      | Main chemical composition                  |
|-----------------------|----------------------|---------------------------|-------------|---------------------------------------|--------------------------------------------|
| Sodium based soil     | 2.69                 | 0.18                      | Yellowish white | Montmorillonite, quartz and quartzite | SiO₂ (65.37%), Al₂O₃ (13.89%), MgO (3.19%), Fe₂O₃ (1.81%), K₂O (1.55%), Na₂O (1.45%), CaO |

Table 1. Physical and chemical properties of raw materials

3
3. Experiment design

3.1 Design of pre-selection mix

Presently, existing systematic research results on buffer/backfill materials are mostly focused on the thermal conductivity of these materials. Therefore, the experiments were designed to develop and identify the anti-seepage performance and shear strength of the mixed material with excellent thermal conductivity. Previous studies have demonstrated that thermal conductivity is optimal when the dry density of the mixed material is ~1.7 g/cm³ and when its moisture content is 20%. However, the addition of a certain proportion of graphite and quartz sand can greatly improve the thermal conductivity of the mixed materials \(^{[17]}\). Therefore, 22 groups of formulas with excellent thermal conductivity were selected as the basic mix ratio in this study. The codes and formulas corresponding to each group are shown in Table 3. Starch, as a common binder, has a wide range of applications. Coupled with suggestions on improving the strength performance of bentonite in other domestic tests, a starch content of 1.15% was realized for the first 22 groups. Thus, pre-selected formulas corresponding to 44 groups were obtained as the optimal mix ratio for the buffer/backfill mixed materials \(^{[24]}\). Table 4 shows the code and formula corresponding to each group.

| Code number | Name | Dry density (g/cm³) | Moisture content | Sanding rate | Graphite content | Zeolite content | Starch content |
|-------------|------|---------------------|------------------|-------------|------------------|----------------|----------------|
| NS1         |      | 1.6                 | 20%              | 10%         | 0                | 0              | 0              |
| NS2         |      | 1.7                 | 20%              | 0           | 0                | 0              | 0              |
| NS3         |      | 1.8                 | 20%              | 0           | 0                | 0              | 0              |
| NS4         |      | 1.8                 | 10%              | 20%         | 0                | 0              | 0              |
| NS5         |      | 1.5                 | 20%              | 20%         | 0                | 0              | 0              |
| NS6         |      | 1.6                 | 20%              | 20%         | 0                | 0              | 0              |
| NS7         |      | 1.7                 | 20%              | 20%         | 0                | 0              | 0              |
| NS8         |      | 1.8                 | 20%              | 20%         | 0                | 0              | 0              |
| NS9         |      | 1.8                 | 20%              | 30%         | 0                | 0              | 0              |
| NS10        |      | 1.8                 | 20%              | 50%         | 0                | 0              | 0              |
| NSM1        |      | 1.7                 | 20%              | 10%         | 5%               | 0              | 0              |
| NSM2        |      | 1.7                 | 20%              | 20%         | 5%               | 0              | 0              |
| NSM3        |      | 1.7                 | 20%              | 30%         | 5%               | 0              | 0              |
| NSM4        |      | 1.7                 | 20%              | 10%         | 10%              | 0              | 0              |
| Code name | Dry density (g/cm³) | Moisture content | Sanding rate | Graphite content | Zeolite content | Starch content |
|-----------|---------------------|------------------|--------------|------------------|----------------|----------------|
| NSM5      | 1.7                 | 20%              | 20%          | 10%              | 0              | 0              |
| NSM6      | 1.7                 | 20%              | 30%          | 10%              | 0              | 0              |
| NSMF1     | 1.7                 | 20%              | 10%          | 5%               | 5%             | 0              |
| NSMF2     | 1.7                 | 20%              | 10%          | 5%               | 10%            | 0              |
| NSMF3     | 1.7                 | 20%              | 20%          | 5%               | 5%             | 0              |
| NSMF4     | 1.7                 | 20%              | 20%          | 5%               | 10%            | 0              |
| NSMF5     | 1.7                 | 20%              | 30%          | 5%               | 5%             | 0              |
| NSMF6     | 1.7                 | 20%              | 30%          | 5%               | 10%            | 0              |

Table 4. New mixture proportion group and sub-table.

3.2 Characterization of the raw materials

To perform thermal conductivity tests, it is necessary that the specimen should have a height of at least 15 mm, while the standard height for the direct shear test is 20 mm. The specimen size required for the heat conduction and strength tests was 60.2 mm × 20 mm; therefore, each single specimen had a volume of 57.5 mm³. To compress the test block required for the tests, a self-designed and customized pressing mold with an inner wall diameter of 60.2 mm and a height of 60 mm was constructed. Considering that during the thermal conductivity tests, at least two text blocks were required, the direct shear tests required at least four test blocks, and during the sample preparation process, material loss was inevitable, and each set of samples was prepared ensuring a total raw material volume of 250 mm³.

To determine the permeability of each pre-selected mix ratio, the test pieces made from each mix ratio were tested using the variable head permeability test. The test specimen size was 60.2 mm × 40 mm, and the target volume of a single specimen was 115 mm³. To compress the required specimens, a self-designed mold, with a size of 60.2 mm × 80 mm was used. Each set of samples was prepared to
have a volume of 130 mm$^3$, considering the inevitable material losses during preparation and processing. In accordance with the volume corresponding to each combination of dry density and moisture content, the total quality of the dry ingredient content of each sample, the quality of the water, and the dry ingredient content of each group were determined. Thereafter the total mass (N) and the quality of the quartz sand drying sodium-based soil (S), graphite (M), zeolite (F), and starch (D) were calculated to two decimal places.

### 3.3 Sample preparation and testing

**1. Material preparation**

The required amounts of sodium bentonite, quartz sand, graphite, and zeolite were placed in an oven and dried to a constant weight. Given that the starch itself is relatively dry and its amount was very small, to ensure the safety of the test, the starch was not dried. For backup purposes, the Beishan water was filtered using a gauze. The dry ingredients were weighed one after the other. Thereafter, they were placed in a small tray and stirred effectively, and to ensure proper mixing, they were placed in a small mixer, and mixed evenly. During the mixing process, the analyzed Beishan groundwater was sprayed evenly into the materials using a small spray bottle. After the mixing, the samples were then stored in a sealed bag, labelled, and placed in the dark for over 48 h, after which they were kept for standby use.

**2. Sample pressing**

The samples were compressed using the variable compaction energy static compaction method. Using the microcomputer control electronic pressure tester with a self-made mold will enhance conduction. The direct shear test and the permeability test of the sample required that the samples should be compressed from a size of 60.2 × 20 mm and 60.2 × 40 mm cylinder, and the sample height should deviate by ± 0.3 mm. After completion, the demolding tool was used to launch the molded sample slowly and measure its size (as shown in Fig. 2), to meet the requirements for sealed samples in sealed bag.

**Figure 2.** Sample compression and comparison.

**3. Data collection**

After the samples were prepared, their engineering characteristics were tested immediately. A DZDR-S thermal conductivity tester and a strain controlled direct shear tester (Engineering Materials Laboratory, PLA Army University of Engineering) were used to determine the thermal conductivity coefficient, internal friction angle, and cohesive force, C, for each group of samples as shown in Fig. 3. The permeability coefficient of each set of samples was tested using a tST-55 infiltration instrument (Civil Engineering Laboratory, Nanjing Forestry University) as shown in Fig. 4.

**Figure 3** DZDR-S thermal conductivity tester and strain controlled direct shear tester.
4. Analysis of test results

4.1 Analysis of thermal conductivity test results

For the thermal conductivity tests, there were 44 groups in total, and in each group, there were four identical specimens. Two specimens in each group were tested for thermal conductivity. Additionally, each pair was tested at different locations three times. After removing the maximum and minimum values from the measurement data, the average value was calculated as the thermal conductivity of the mix ratio of the group. Considering the test data, the results of the analysis were as follows.

(1) Effect of starch on thermal conductivity

As shown in Fig. 5, the thermal conductivities corresponding to the 44 mix ratios were generally above 1.3 W/m·K, which meets the International Atomic Energy Agency (IAEA) requirement for buffer/backfill materials (> 0.8 W/m·K). Under the same conditions, the starch mix ratio showed a generally higher thermal conductivity. Regarding non-metallic materials, the thermal conductivity coefficients of solids are greater than those of liquids, which are greater than those of gases [17]. Given the small size of the starch particles, they could fill the gaps in the original material that could not be filled by graphite. This resulted in an increase in the contact area between the particles, and owing to the water expansion effect, the starch to a certain extent also fill the small spaces inside the specimens, thereby enhancing their internal compactness. Therefore, the addition of starch enhanced the thermal conductivity of the original 22 mix ratios to varying degrees.

(2) Relationship between thermal conductivity and dry density (D)

To verify the influence of dry density on the thermal conductivity of the mixed buffer/backfill materials, dry density was considered as the independent variable, and representative data were selected for analysis as shown in Fig. 6, in which "Rs" and "Rd" represent the sand mixing rate and starch content, respectively.

Additionally, Fig. 6 shows that under the same conditions, the thermal conductivity of the mixed material increased as the dry density increased. Comparing curves 1 and 3 or 2 and 4 showed that the thermal conductivity of the composites with a sand mixing ratio of 20% was better than that with a sand mixing ratio of 10%.
Figure 5. Curve showing the effect of starch on thermal conductivity.

Figure 6. Curve showing the relationship between thermal conductivity and dry density.

(3) Relationship between thermal conductivity and admixture content

To verify the effect of the sand mixing rate on the thermal conductivity of the new buffer/backfill materials, the independent variable was the content data corresponding to each admixture as shown in Fig. 7, in which "RM", "RF", and "Rd" represent graphite, zeolite, and starch contents. Observing the curves revealed that the thermal conductivity increased as the sand mixing rate increased. Additionally, to simultaneously verify the effect of the sand mixing ratio on the thermal conductivity coefficient, the effects of graphite and zeolite contents on the thermal conductivity of the composite material were also investigated. From Fig. 7(b), considering curves 1 and 3 or 2 and 4 showed that when other variables remained unchanged, the composite material with a graphite content of 0.1% had a thermal conductivity coefficient that was obviously higher than that of the composite with a graphite content of 0.05%. Therefore, the addition of a small amount of graphite to enhance the thermal conductivity coefficient of the composite material had a significant effect. Considering Fig. 7(c), curves 1 and curve 3 or 2 and 4 showed that for zeolite to improve the thermal conductivity of the composite material, a certain reaction, such as boiling was necessary. However, considering that zeolite has good adsorption and ion exchange properties, as well as acid proof heat-resisting performance, it is often used as an auxiliary material for hybrid buffer/backfill materials[17].

Figure 7. Curves showing the relationship between thermal conductivity and admixture content.
4.2 Analysis of penetration performance test results

In this test, the variable head permeability test was performed on the selected 44 groups of mixed ratio standard specimens. Due to the extremely low permeability of the mixed material, the data were observed twice a day during the test after the flow rate became stable. The seepage flow rate during this period was obtained to calculate the permeability coefficient of the mix ratio corresponding to each group. Considering the effect of temperature on the permeability of the materials, the measured permeability coefficient was calibrated using the dynamic viscosity coefficient of water, and the standard permeability coefficient of each mix ratio at 20 °C was obtained as the final permeability coefficient of the mix ratio.

(1) Effect of starch content on the permeability coefficient

To determine the effect of the starch content on the permeability of the mixed buffer/backfill material, all the 44 specimen groups were divided into two groups based on the absence or presence of starch. With the exception of the starch content, the formulas with corresponding numbers in the two groups were similar. Curves showing the effect of the addition of starch on the permeability of the composites are shown in Fig. 8.

From this figure, it is evident that the permeability coefficient of most of the mix ratios had magnitudes in the range 10–13 m/s, while that of some specimens could reach magnitudes in the range 10–14 m/s, meeting the requirements of the IAEA on the permeability performance of buffer/backfill materials. Comparing the two curves showed that adding a small amount of starch into the mixed material could enhance the compactness of the specimen, hinder the seepage action of water, and reduce the permeability coefficient to a certain extent.

(2) Effect of dry density (D) on the permeability coefficient

To study the effect of dry density on the permeability coefficient of the mixed materials, dry density was used as the independent variable to select the mix ratio for analysis. Fig. 9 shows the variation of the relationship between the permeability coefficient and dry density.

![Figure 8. Curve showing the effect of starch on permeability.](image1)

![Figure 9. Curve showing the relationship between permeability coefficient and dry density.](image2)

From Fig. 9, it is evident that an increase in the dry density of the composite resulted in an increase in the compactness of the specimen. Thus, the permeability coefficient decreased to varying degrees. Specifically, the permeability coefficient decreased as the dry density increased. Comparing curves 1 and 2 or 3 and 4 showed that to a certain extent, starch could promote a decrease in the permeability coefficient, which at a sand mixing ratio of 20%, was found to be higher than that with a sand mixing ratio of 10%.

(3) Effect of admixture content on the permeability coefficient

To explore the effect of the content of the admixture on the permeability coefficient, these two variables were selected as the main variables for the analysis. The curve showing the relationship between the obtained permeability coefficient and the admixture content is presented in Fig. 10.
From this figure, it is evident that the permeability coefficient of the mixed material first of all increased, and thereafter decreased as the sand mixing ratio increased. Particularly, the peak value of the permeability coefficient was obtained when the sand mixing ratio was ~20%. The permeability coefficient of the composite material with starch was significantly lower than that of the composite without starch. Considering curves 1 and 3 or 2 and 4 (Fig. 10(b)), it became evident that the permeability coefficient of the mixed materials increased slightly as their graphite contents increased. Curves 1 and 3 in Fig. 10(c) showed that the permeability coefficient of the composite materials at a zeolite content of 0.1% was lower than that at a zeolite content of 0.05%. Conversely, curves 2 and 4 did not obviously exhibit this phenomenon. Additionally, curves 1 and 3 corresponded to composites without starch; thus, zeolite acted as the main material bonding agent. On the other hand, curves 2 and 4 correspond to composites without zeolite, but have a starch content of 1.15%. This observation implies that both starch and zeolite have a certain binding effect, and mixing them hindered the effect of zeolite. Generally, a certain amount of zeolite can reduce the permeability coefficient of the mixed materials, thereby enhancing their impermeability.

**Figure 10.** Curves showing the relationship between the permeability coefficient and the sand mixing ratio.

### 4.3 Analysis of strength performance test results

To test the shear strength of the different mixture composites, direct shear tests was performed on the 44 groups of the standard specimens with different mixture ratios. Each group of four identical specimens were compressed, and thereafter, the mixture ratio was tested to obtain the shear displacement of the specimens under normal loads of 100, 200, 300, and 400 kpa. The shear stress
corresponding to each shear displacement was calculated, and the internal friction angle and cohesion force, C, corresponding to the mix ratio of each group were obtained by fitting 4 shear stresses.

(1) Effect of starch on strength performance

To determine the effect of the addition of starch on the shear strength of the mixed materials, the strength indexes obtained from all the 44 groups were classified under two large groups depending on the absence or presence of starch. It was observed that the formulas of the corresponding numbered specimens in each group were consistent for other variables except for the starch content. The relationship between the starch content of the mixed materials and the internal friction angle and the cohesion force, C, of the specimens obtained using each formula, are shown in Fig. 11(a) and 11(b), respectively.

As shown in Fig. 11, starch contents up to 1.15% could improve the internal friction angle and cohesion force of the mixed materials to varying degrees. Thus, the shear strength improvement-effect resulting from a starch content up to 1.15% could not be neglected.

(2) Effect of dry density (D) on the intensity index

Dry density is one of the indexes that has a significant effect on the formula of mixed buffer/backfill materials, and for comparative analysis, the strength index of part of the mixture ratio was selected as the independent variable. The curve showing the relationship between the strength index and the dry density is illustrated in Fig. 12. Particularly, from Fig. 12(a) and (b), it is evident that as the dry density increased, the cohesive force as well as the internal friction angle of the specimens showed an increasing trend.

(3) Relationship between strength index and admixture content

To determine the effect of the sand mixing ratio on the strength performance of the mixed buffer/backfill materials, the strength index of the mixing ratio was chosen based on the formula of the
44 specimen groups, considering the content of each admixture as the main variable for the comparative analysis. The curves showing the variation in the relationship between the obtained strength index and the content of each admixture are shown in Fig. 13–15.

From these figures, it is evident that the cohesion force of the mixed material decreased as the sand mixing ratio increased. Additionally, the internal friction angle first increased, and then decreased as the sand mixing ratio increased. When the sand mixing ratio was ~20%, the peak internal friction angle value was observed. Comparing the different curves showing the variation of starch content revealed that the addition of starch could significantly improve the strength index of the mixed materials. Further, comparing curves 1 and 3 or 2 and 4 in Fig. 14(a), it was evident that the internal friction angle of the mixed materials increased with increasing graphite content. Curves 1 and 3 or 2 and 4 in Fig. 14(b) also showed that the cohesion force of the mixed materials increased with increasing graphite content. Furthermore, comparing curves 1 and 3 or 2 and 4 in Fig. 15(a) showed that the internal friction angle of the mixed material decreased with increasing zeolite content, and curves 1 and 3 or 2 and 4 in Fig. 15(b) showed that the cohesive force of the mixed material increased with increasing zeolite content.

![Variation of strength index in the first group with the sand mixing ratio.](image1)

![Variation of strength index in the second group with the sand mixing ratio.](image2)
Conclusions
In this study, the engineering characteristics of a proposed preselection scheme for the optimal mixture ratio for mixed buffer/backfill materials were evaluated. Based on the results obtained, the following conclusions could be made:

1. As a commonly used binder, starch can improve the compactness of mixed buffer/backfill materials, increase the contact area between the particles in the material, and improve the thermal conductivity, impermeability, and strength of the material to varying degrees.

2. The results obtained showed that all the mixture ratios met the requirements of the IAEA with respect to thermal conductivity. Particularly, the thermal conductivity of the mixed materials increased with increasing sand mixing ratio, dry density, and graphite content, but decreased slightly with increasing zeolite content.

3. All the mixture ratios met the IAEA's requirement that the permeability coefficient of buffer/backfill materials should not be greater than 10–13 m/s. The permeability coefficient of the mixed materials decreased as their dry densities and graphite contents increased. Additionally, as the sand mixing ratio increased, the permeability coefficient first increased, and thereafter, decreased. Particularly, when the sand mixing rate was 20%, the permeability coefficient of the materials was maximum.

4. The internal friction angle and cohesion force of the mixed materials increased as their dry densities, starch contents, and graphite contents increased. However, as their zeolite contents increased, their internal friction angle decreased, while their cohesive force increased. As their sand mixing ratio increased, their internal friction angle first increased, and thereafter decreased as the sand mixing rate further increased. Additionally, when the sand mixing ratio reached a peak value of 20%, the cohesion force decreased as the sand mixing ratio further increased.

5. Taking the above conclusions into consideration, the engineering requirements for buffer/backfill materials in the reference disposal repository should be screened in accordance with the principle of "lead heat, re-penetration, and post-strength". Additionally, considering that starch is an organic substance, it is necessary to study and verify its physicochemical stability with respect to the long-term stability of the disposal repository. Finally, it was determined that specimens NSM4 and NSMFD5 are the recommended optimal mix ratio schemes for buffer/backfill materials for application in geological disposal repositories for high-level radioactive waste.

Reference
[1] PUSCH R. Highly compacted sodium bentonite for isolating rock-deposited radioactive waste products[J]. Nuclear Technology, 1979, 45(9): 153–157.
[2] Zhang Hua-zhu. Geological disposal of high-level radioactive waste in China: current situation and prospect [J]. Uranium geology, 2004, 20(4) : 193-195.
[3] Xu Guo-qing. Study on geological disposal of high-level radioactive waste in Canada and the United States [J]. Foreign uranium and gold geology, 2001, 18(3) : 169-175.
[4] Lopez R.S., Cheung S.C.H., Dixon D.A. The Canadian program for sealing underground nuclear fuel waste vaults [J]. Canadian Geotechnical Journal, 1984, 21(3) : 592-596.
[5] Braithwaite J.W, Molecke M.A. High-Level waste canister corrosion studies pertinent to geologic isolation [J]. Nuclear Waste Management and Technology, 1979, 1(1) : 37-50.
[6] OECD. Engineered Barrier Systems and the Safety of Deep Geological Repositories State-of-the-art Report[R]. Paris: Radioactive Waste Management Committee, 2003: 21-22.
[7] Nuttall K., Urbanic V.F. An Assessment of Materials for Nuclear Fuel Immobilization Containers[R]. Manitoba: Atomic Energy of Canada Limited, 1981.
[8] Mckay P., Mitton D.B. An electrochemical investigation of localized corrosion on Titanium chloride environments [J]. Corrosion, 1985, 41:52-62.
[9] Pusch R. Highly compacted sodium bentonite for isolating rock-deposited radioactive waste products[J]. Nuclear Technology, 1979, 45:153-157.
[10] TANG A M, CUI Y J, LE T T. A study on the thermal conductivity of compacted bentonites[J]. Applied Clay Science, 2008, 41(3) : 181-189.
[11] CUI Y J, TANG A M. On the thermal conductivity of compacted MX80 clay[C]// CUI Y J, YE W M, CHEN B ed. Proceedings of the International Symposium on Engineered Barriers for High-level Radioactive Waste Disposal. Shanghai: [s.n.], 2005 : 121-131.
[12] PACOVSKY J. Some results from geotechnical research on bentonite[C]// KONVALINKA P, LUXEMBURK F, ed. CTU Reports : Experimental Investigation of Building Materials and Technologies. [S.l.]: [s.n.], 2002 : 107-116.
[13] Zhu Guo-ping, Liu Xiao-dong. Thermal properties of bentonite in Inner Mongolia [J]. Resources, environment and engineering, 2005, 19(3) : 220-222.
[14] Ye W M, Borrell N C, Zhu J Y, et al. Advances on the investigation of the hydraulic behavior of compacted GMZ bentonite [J]. Engineering Geology, 2014, 169:41-49.
[15] Ye W M, Chen Y, Chen B, et al. Advances on the knowledge of the buffer/backfill properties of heavily- compacted GMZ bentonite [J]. Engineering Geology, 2010, 116(1-2) : 12-20.
[16] Liu y m, Chen z r. feasibility of Inner Mongolia gaomiaozi bentonite as backfill material for high-level waste disposal repository [J]. Acta mineralogica sinica, 2001, 21(3) : 541-543. (in Chinese).
[17] Ji Lei, Li Er-bing, XU Ao-ni, et al. Thermal conductivity test of mixed buffer backfill materials [J]. Acta Mineralogica Sinica, 2008, 38(4) : 429-436.
[18] Cui Y J, Loiseau C, Delage P. Water transfer through a confined heavily compacted swelling soil[C]//Proceedings of 1st World Forum of Chinese Scholars in Geotechnical Engineering, Shanghai, China. 2003, 1218.
[19] Cao sheng-fei, Liu Yue-miao, et al. Error analysis and feasibility study of bentonite permeability test [J]. Journal of rock mechanics and engineering, 2010, 29 (add 2) : 4200-4207.
[20] Zhang Hu-yuan, LU Qing-feng, WANG Bao, et al. Permeability and Testing of bentonite buffer materials [C]. Proceedings of the Inaugural Meeting of The Waste Underground Disposal Committee of The Chinese Society of Rock Mechanics and Engineering and the First Academic Exchange Conference, 2006:93-98.
[21] Zhang Hu-yuan, Wang Xue-wen, Liu Ping, et al. Research on seam sealing and healing of buffer backfill material block [J]. Journal of rock mechanics and engineering, 2016, 35 (add 2) : 3605-3614.
[22] Liang J. Study on compaction performance of Mixed buffer backfill materials [D]. Lanzhou: Lanzhou University, 2009.
[23] Jia L Y. Study on shear strength characteristics of Mixed buffer backfill materials [D]. Lanzhou: Lanzhou University, 2013. (in Chinese)
[24] Luo ping, et al. Preparation of bentonite particles and study on the adsorption property of chromium in wastewater [J]. Nonmetallic ore, 2014, 37 (2) : 72-78. (in Chinese)
[25] Sun D An, ZHANG Gan-yue, ZHANG Long, et al. Experimental Study on strength Timeliness of Gaomiaozi Bentonite [J]. Rock and Soil Mechanics, 2008, 39(04) : 1-6.
[26] Liu Yue-miao, Wang Ju, Cao Sheng-fei, et al. Study on thermal - water-force - chemical coupling properties of large test bed and buffer materials for geological disposal of high-level radioactive waste in China [J]. Rock and soil mechanics, 2013, 34 (10) : 2756-2789.