Compressibility and compressive strength of the modified removed soil from decontamination projects in Fukushima

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ABSTRACT

An estimated volume of 14 million m$^3$ of the removed soil and waste generated from decontamination projects in Fukushima Prefecture is being transported to the interim storage facility at present. Modification agents such as water-absorbing polymer are used to improve the treatability of the removed soil for efficient separation of foreign materials. It is expected that the modified removed soil can be reused as geomaterial to reduce the final disposal volume under the major premise of safety assurance. Thus, it is important to understand the mechanical properties of the modified removed soil and the influence of the modification agents. This study focused on the compressibility and the unconfined compressive strength of the modified removed soil. Compression tests using oedometer and unconfined compression tests were conducted on the removed soil modified with a water-absorbing polymer powder agent and the mix proportion by weight was 3% and 10%. Decomposed granite soil was used as a comparison. With addition of 10% polymer agent, the final settlement of the modified removed soil decreased by 20% and the unconfined compressive strength increased by 80% to 82 kN/m$^2$. The results suggest that the mechanical performance of the modified removed soil might be improved with a certain amount of polymer agent addition.

Keywords: removed soil, polymer modify agent, compressibility, unconfined compressive strength

1 INTRODUCTION

On March 11, 2011, a tremendous earthquake of a 9.0 magnitude struck Japan and triggered a massive tsunami that hit the northeastern coast. The earthquake and the ensuing tsunami damaged the facilities of Fukushima Daiichi Nuclear Power Station (NPS) of Tokyo Electric Power Company Holdings (TEPCO) and resulted in the release of a large amount of radioactive materials into the atmosphere (TEPCO, 2013), which was carried by wind currents and descended to the ground with rain, etc., and contamination was observed in a wide area, mainly in Fukushima Prefecture (Ministry of the Environment of Japan (MOE) 2018).

Decontamination projects are being implemented in those affected regions since 2012. Radioactive materials were removed from the inhabitation areas in order to promptly reduce the impact on human health and the environment. At present, an estimated volume of 14 million m$^3$ of the removed soil and waste (MOE 2019a) is being transported to the interim storage facility (ISF) and will be stored there until the final disposal outside Fukushima Prefecture within 30 years. Considering the huge volume, it is very difficult to secure such a large scale of the final disposal sites to contain all the removed soil and waste. Therefore, reuse of the removed soil with relatively low-level radioactivity as a geomaterial for the construction of embankments or other purposes is expected to reduce the final disposal volume.

It was reported that the removed soil from farmlands contains large amount of cohesive soil mixed with organic matters which are hard to be separated (Inui et al. 2016). In addition, clogging of soil on the sieve during screening process in the ISF as shown in Fig. 1 will greatly reduce the separation efficiency (Asada et al. 2018). Thus, modify agent such as water-absorbing polymer powder is used to optimize the treatability of the removed soil. Polymer agent can quickly absorb free water in the soil and become gelatinous after being added. The appearance of the modified removed soil will become loose and dry. As a result, the separation efficiency will be improved and continuous handling of large volumes of the removed soil become possible.

Meanwhile, the properties of the modified removed soil have not been fully investigated and the impact of water-absorbing polymer agent remains unclear. Since the environmental safety is a crucial factor for the reuse
of the modified removed soil as a geomaterial, it is important to understand its mechanical properties to ensure that the structures using this material are stable and safe. This is a preliminary study focused on the compressibility and the unconfined compressive strength of the modified removed soil. Compression test using an oedometer and unconfined compression tests were conducted on the modified removed soil and influence of the addition of water-absorbing polymer powder on the mechanical performance was evaluated.

2 BACKGROUND

There are several methods in decontamination projects such as scraping top soil for a few centimeters, removing sediments, branches and leaves, washing with water, etc., and the objects include buildings, roads, soils, vegetations and reservoirs. Whole area decontamination excluding the Difficult-to-Return Zones was completed on March 19, 2018 and approximately 16.5 million m³ of the removed soils and waste was generated in Fukushima Prefecture. The removed soil and waste were packed into container bags and stored on site or being brought to approx. 1300 temporary storage sites at first. Combustible waste was sent to temporary incineration facilities and the incinerated ash, together with the removed soil, are being transported to the interim storage facility which is located surrounding the TEPCO Fukushima Daiichi NPS.

As of October 2019, 4 million m³ of the removed soil and waste had been transported, among which the volume of soil is 93.7%, incinerated ash is 1.7% and the combustible material after separation is 4.0%. It is estimated that the total volume of removed soil is around 13 million m³, among which sandy soil is around 7 million m³ (from residential area, school and park, etc.) and cohesive soil is around 6 million m³ (from farmland and forest, etc.).

Researches and demonstration projects have been carried out towards the final disposal of the removed soil and waste considering the effect of radioactive decay and the potential of volume reduction and recycling. The basic concept is that the removed soil will be treated by volume reduction technology such as classification, chemical or heat treatment to lower the contamination level and reused as a geomaterial under appropriate management. The use should be limited to the public projects which is not assumed to change shape artificially for a long time period, e.g. basic structure material of banking for coastal levees or seaside protection forests, embankment materials for roads, cover soil for waste disposal sites, etc. (MOE 2019b).

Since organic matters such as weeds and roots were contained in the removed soil, water-absorbing polymer agent was applied to promote the separation and improve the treatability of the removed soil. It achieves better handling ability comparing to gypsum and has neutral pH which is more environmental-friendly comparing to quicklime (Asada et al. 2018). Water-absorbing polymer has been widely used in hygienic and agricultural areas however its application in geotechnical filed is rare so far. The swelling characteristic after absorbing water might affect the stability and strength of the structure using the modified removed soil. In addition, the environmental safety should also be investigated since the leaching behavior might also be affected. Therefore, it is necessary to study the properties of the modified removed soil after this pretreatment process.

There are a few studies focus on the soil structure after modification using X-ray CT scan (Tanaka et al. 2019, Shimizu et al. 2019). However, other researches on the modified removed soil is limited so far. The physical and chemical properties of water-absorbing polymer modified removed soil remains unclear. A comprehensive understanding on the impact of polymer agent on the soil will not only contribute to the reutilization of modified removed soil but also promote the application of this material on treating other high-water-content material such as sludge from construction site.

3 MATERIALS AND METHODS

3.1 Removed soil and polymer modify agent

Removed soil used in this study was obtained from a temporary storage site in Iitate village, Fukushima Prefecture. Soil particles passing a 4.75 mm-opening sieve were used and the initial water content is around 49%. The soil particle density (ρp) is 2.33 g/cm³ and the maximum dry density is 1.09 g/cm³. The total organic carbon content is 95.3 g/kg. The major radioactive contaminants are radioactive Cesium (Cs)-134 and Cs-137. The radioactivity level of this removed soil is around 11704 Bq/kg.

Polymer modify agent used in study was supplied from Leafair Co., Ltd. It is a kind of water-absorbing polymer powder and the initial water content is around 10%. Its swelling property was estimated based on the Japan Bentonite Manufacture Association Standard
(JBAS-104-77). 2g agent was added into a 100 mL measuring cylinder filled with 100 mL distilled water by 10 times. The cylinder was sat undisturbed for 24 hours and then the volume level (mL) of the gelatinous material was recorded.

It turned out that the total 100 mL distilled water became gelatinous immediately after 2 g agent was added. Thus, another case was conducted and only 0.06 g agent was added. The result was 12 mL/0.06 g, suggesting that 1 g agent is capable of absorbing 400 mL water and turn it into gel.

To prepare the soil-agent mixture, the removed soil was mixed with polymer agent by 3% and 10% of its natural weight. Polymer agent powder was added into the removed soil and was manually mixed. The water content of the mixture was measured immediately after mixing using a microwave oven.

3.2 Compression test using an oedometer

Compression tests were conducted using the experimental apparatus originally for high-temperature consolidation test. Specimen was compressed by a loading plate which is connected to an air cylinder on top through a load cell. Compression load is controlled by the computer program. Compression pressure and the settlement of the specimen was measured by transducers and recorded automatically during test.

The dimension of the specimen is 6 cm in diameter and 5 cm in height. Prepared material was compacted in the oedometer in 5 layers. For original removed soil (0%), the weight of the specimen was calculated based on the natural water content to make sure that the dry density of the specimen equals to 0.85 of the maximum dry density. For modified soil, the dry density of soil-agent mixture was considered instead.

In addition, a set of contrast test was conducted using decomposed granite (DG) soil ($\rho_d = 2.44$ g/cm$^3$). The mix proportion remained same (0%, 3% and 10%) and the initial water content of DG soil was adjusted to 10.6% (optimum water content) first before mixing with polymer agent powder. During compaction, the dry density of DG soil alone was considered. Thus, the weight of DG soil was same in each case and it was expected that the impact of polymer agent can be highlighted.

The compression pressure started from 9.8 kN/m$^2$ to 628 kN/m$^2$ with 8 stages and the load increased twice for each stage (load increment ratio $\Delta p/p = 1$). The loading time is 3 min for each stage and the data was measured every 3 seconds. Before the first stage of 9.8 kN/m$^2$, a compression pressure of 3 kN/m$^2$ was loaded for 10 seconds and this pre-stage compression was considered as the zero point for settlement.

As for the calculation of the void ratio, it was assumed that the polymer powder and water fully converted into gel and only the soil particles were considered as solid. The initial void ratio for each test case was summarized in Table 1.

### Table 1. Initial void ratio of all test cases.

|                | 0%   | 3%   | 10%  |
|----------------|------|------|------|
| Removed soil   | 1.54 | 1.59 | 1.87 |
| Decomposed granite soil | 0.52 | 0.53 | 0.54 |

3.3 Unconfined compression test

Unconfined compression tests were conducted according to JIS A 1216 “Method for unconfined compression test of soils”. Removed soil and soil-agent mixture under the mix proportion of 3% and 10% was used in this test. For each case, the tests were conducted in duplicate.

The dimension of the specimen is 5 cm in diameter and 10 cm in height. The prepared material was compacted in a plastic cylindrical mold in 5 layers. The compaction degree was same as compression test which was previously described in 3.2.

After compaction, specimen was taken out of the mold without curing and the test was conducted immediately. The load and displacement were measured and converted into compressive stress and strain automatically by the computer program.

4 RESULTS AND DISCUSSION

4.1 Compressibility

For the original removed soil and the modified removed soil with addition of water-absorbing polymer powder by 3% and 10%, variation of the coefficient of volume compressibility ($m_v$) with average compression pressure was shown in Fig. 2.

The $m_v$ of the removed soil is larger than the $m_v$ of 3% and 10% case except for the average compression pressure of 444 kN/m$^2$. The decrease of $m_v$ after modification was probably because the free water in the soil became gel when it was absorbed by polymer agent, which made the soil-agent mixture less compressible.

The $m_v$ of 3% and 10% case was similar for the average compression pressure lower than 100 kN/m$^2$, which suggests that low compression pressure might have little effect on gel. On the other hand, when the average compression pressure was 111 and 222 kN/m$^2$, the $m_v$ of 10% case became lower than 3% case. Higher

![Fig. 2. Settlement-time curve of removed soil cases.](image-url)
additional amount of polymer agent might generate more gels in the soil, which contributed to the resistance of deformation under higher compression pressure. The compressibility of the two cases became close again for average compression pressure of 444 kN/m² and was similar with the original soil, suggesting that the compression on soil particles might be the main process in the final loading stage.

The variation of settlement with time at each loading stage for all removed soil cases were shown in Fig. 3. For 3% case, there was a settlement of 0.99 mm during the first 10-second compression of 3 kN/m², which was not observed in other two cases. The reason was not clear, and the result is needed to be verified in the future.

The final settlement of the removed soil without modification was 10.6 mm. Addition of 3% polymer agent reduced the final settlement to 10.2 mm and addition of 10% polymer agent further reduced the final settlement to 8.5 mm. Therefore, addition of polymer agent can mitigate the settlement of removed soil and the effect increases with increasing addition amount.

For decomposed granite soil, the variation of settlement with time was shown in Fig. 4. The final settlement for the DG soil and the soil-agent mixture with 3% and 10% polymer addition was 4.9 mm, 3.4 mm and 4.0 mm respectively. The final settlement decreased after modification, which was consistent with the results of the removed soil cases. Therefore, it is effective to reduce the settlement of soil by using water-absorbing polymer as the modification agent.

It should be noticed that the final settlement of 10% case is larger than 3% case, thus the mitigation effect did not increase with the increasing content of modify
agent for DG soil. One possible explanation is that there are more gelatinous substances generated in 10% case which probably covered the soil particles and broke the bond in the specimen instead of just filling the voids. Soil-agent mixture of 10% case became more compressible compared to 3% case. Another possible explanation is that the swelling of polymer powder might be limited in 10% case due to the relatively low water content of DG soil. The free water distributed in the specimen might not be enough for the agent to fully swell and the gels were more compressible which resulted in a larger settlement.

Coefficient of volume compressibility of 3% and 10% case shown in Fig. 5 had similar variation trend for average compression pressure lower than 100 kN/m² and was smaller than 0% case. It can be attributed to the effect of gel generated during modification since the addition amount of polymer agent was the only difference among these cases. The compression on soil probably started to have the major impact instead of the voids afterwards and the $m$ of the three cases became similar.

The compression curves for all cases were shown in Fig. 6. Modification by polymer agent reduced the compressibility for both removed soil and decomposed granites soil. The effect of addition amount of polymer agent was not obvious under low compression pressure of 100 kN/m². For removed soil, the effect of polymer agent addition became more obvious with increasing of compression pressure. However, addition of polymer agent became less effective for compression pressure over 100 kN/m² for sandy soil like decomposed granite soil with low initial water content. It was assumed that compression on soil had a major impact instead.

4.2 Unconfined compressive strength

For unconfined compression tests, the stress-strain curves for all test cases are shown in Fig. 7. The average value for the unconfined compressive strength and failure strain of the duplicate specimens were summarized in Fig. 8. Both unconfined compressive strength and failure strain increase with increasing addition amount of polymer agent.

For modified removed soil, the specimens used in the tests were compacted into the mold based on the dry density of the soil-agent mixture instead of soil alone, which was equal to the 0.85 of maximum dry density of soil. Thus, the mass of removed soil decreased in the compacted specimens for 3% and 10% case which part was replaced with the gel generated by polymer agent and water.

Increased unconfined compressive strength and failure strain suggests that the gelatinous substance offered higher strength and viscosity compared to soil.
particles. The voids of the specimen were probably filled and the bond among soil particles became stronger. In addition, some fine particles might aggregate after modification which may also contribute to the increase of compressive strength.

It should be noticed that the increasing of unconfined compressive strength was not linear. The gelatinous substances generated in 10% case might partially broke the bond of soil particles which is similar to the compression test result of decomposed granite soil mixing with 10% polymer agent. Since the removed soil has a higher initial water content, it can be assumed that there was still enough free water to be involved in the reaction with polymer agent. Further study is necessary to investigate the change on the microstructure of soil after polymer agent modification.

5 CONCLUSIONS

This research was conducted to evaluate the compressibility and compressive strength of removed soil obtained from decontamination projects modified by water-absorbing polymer agent powder.

Compression tests using oedometer and unconfined compression tests were conducted on the removed soil, and the soil-agent mixture with a mix proportion of 3% and 10% based on natural weight. Decomposed granite soil was also used in compression test.

After addition of 10% polymer agent, the final settlement of removed soil decreased from 10.6 mm to 8.5 mm and its unconfined compressive strength increased from 45.3 kN/m² to 81.66 kN/m². Mechanical performance of the removed soil was improved by polymer agent modification.

For compression test, modification by polymer agent reduces the compressibility for both removed soil and decomposed granites soil. The effect polymer agent amount is not obvious under low compression pressure of 100 kN/m². For the removed soil, the effect of polymer agent addition became more obvious with increasing of compression pressure. For decomposed granite soil, modification became less effective when compression pressure was over 100 kN/m² and soil mixing with 10% agent exhibited larger settlement compared to 3% case. A smaller addition of polymer agent might obtain a better effect if the initial water content of the original soil is relatively low.

For unconfined compression test, unconfined compressive strength and failure strain increases with increasing addition amount of polymer agent. The gelatinous substance generated by polymer agent and water probably offered higher strength and viscosity.

This is a preliminary study to investigate the properties of the modified removed soil and study the impact of water-absorbing polymer agent in order to reuse them safely and effectively in the future instead of final disposal. Further studies will be conducted to evaluate the environmental safety and mechanical performance of the modified removed soil. The mechanism of the polymer modification and the interaction among soil, water and polymer will be studied.

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