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INFLUENCE OF PREPARATION CONDITIONS ON SOLIDIFIED-CRUSHED SOIL CHARACTERISTICS AND STRENGTH

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ABSTRACT: When the soil generated during road or river excavation work is too soft to be used as a material, it can be improved by the use of solidifiers such as cement and lime. However, if an embankment has excessive strength as a result of solidification, the embankment may be difficult to re-excavate. High-strength embankments may fail if they are constructed on soft ground and are not able to follow the behavior of that ground. For this reason, there is a demand for a material whose strength development can be controlled even when a solidifier is added. As a solution to this issue, we investigated the use of crushed solidified soil. Crushed solidified soil is produced by adding a solidifier to soil and then crushing the soil in the middle of the solidification process. It is considered that the type and amount of solidifier and the timing for crushing have considerable influence on the physical properties and strength of the product. Therefore, we investigated the physical properties and strength of the crushed solidified soil and constructed two types of full-scale embankments on soft ground. We compared the deformation characteristics of these two embankments. We found that the crushed solidified soil had lower strength than the solidified soil and that the physical properties and strength of the material depended on the time elapsed before crushing of the solidified soil. Furthermore, it was found that the embankment by solidified crushed soil follows the deformation of soft ground.

Keywords: Solidified crushed soil, Production conditions, Physical properties, Strength

1. INTRODUCTION

Soil that is generated during road and river excavation is too soft for reuse in embankment construction can be improved by solidification using solidifiers such as cement or lime [1]. Be able to improve soft soil by using this method; however, the strength of an embankment constructed using this type of improved soil may exceed the required value. If the strength of an embankment constructed using the solidified soil is exceedingly high due to solidification, it may be difficult to re-excavate the embankment when installing median strips or guardrails. High strength embankments may fail when they are constructed on soft ground and are not able to accommodate the behavior of the soft ground.

For these reasons, the crushed solidified soil was investigated, which is produced by mixing a solidifier in soft soil and then crushing it in the middle of the solidification, as a material whose strength development is possible to control even when a solidifier is mixed [2,3]. Also the strength and compaction characteristics of the solidified crushed soil affect the type, amount of the solidifier, and the leaving time from the mixing of the solidified material to the crushing. Investigated the physical properties and strength of crushed solidified soil produced using volcanic ash depending on the amount of solidifier, time for leaving still before crushing, and the curing time. Furthermore, two full-scale embankments were constructed on soft ground and investigated their deformation. The original soil for these embankments was clay. One embankment was constructed using solidified soil, and the other was constructed using the crushed solidified soil. This paper summarizes the investigation results.

2. CRUSHED SOLIDIFIED SOIL

The crushed solidified soil is a soil material produced by mixing a solidifier in an original soil that requires solidification and crushing it after a certain length of time. The crushed solidified soil can be used in construction that involves compaction. The strength characteristics of the compacted crushed solidified soil differ depending on the time between solidification and crushing. When the time before crushing is short, the solidification process has not been completed, and the constructability is inferior because the strength development is low at compaction. The solidification ability of this type of crushed solidified soil is still maintained after compaction. Therefore, the strength develops further after curing for a certain length of time, during which the solidification reaction progresses. When the time before crushing is long, crushing is done for soil that has already developed a certain degree of strength; therefore, the constructability is good. The residual ability to develop solidification in the crushed soil

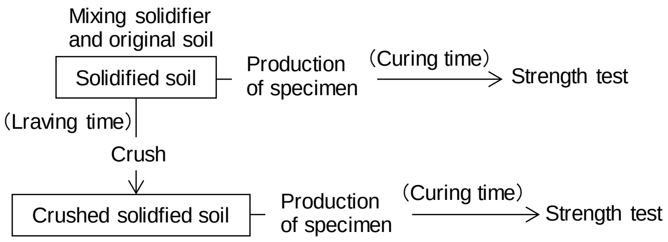

Fig.1 Defined of term

is smaller than that of the soil with a shorter time before crushing, and the increase in the strength after compaction is small.

The terms used in this report are defined as shown in Figure 1.

Solidified soil: A mixture of the solidifier and the soil subject to improvement (original soil).

Leaving time: The time between the mixing of the solidifier in the original soil and the crushing.

Crushed solidified soil: A soil material produced by crushing the solidified soil.

Curing time: The time between the production of a specimen and the strength test for solidified soil and crushed solidified soil.

3. TEST METHOD

Table 1 shows the basic physical properties of original soil No.1, which was used in testing the physical properties and strength of the crushed solidified soil, and No. 2, which was used for constructing full-scale embankments. Original soil No. 1 used for the physical properties and strength tests was volcanic ash sand and had a high cone index. The original soil used for constructing full-scale embankments was clay with a high liquid limit, whose cone index was very low, and construction machines were not able to travel on it [4].

3.1 Physical Properties and Strength Tests

The tests for physical properties and strength were done at the Tomakomai Construction Test Field of the Civil Engineering Research Institute for Cold Region. The wet weight of original soil No. 1, which was put in a container of 1m3, was measured. Portland blast-furnace slag cement B was added to the original soil. The ratios of the added soil improvement material for the specimens were 5%, 10%, and 15% in the dry weight ratio. Each specimen was mixed for about 10 minutes in the backhoe bucket. An embankment of 50 cm in height and 1 m in crest width was constructed for each specimen. The embankment was formed by pressing the soil with the backhoe bucket. These embankments were left at the open test field under natural weather conditions. The test specimens for each solidified soil was produced by using the backhoe bucket and the backhoe breaker and breaking the part of the embankment into crushed solidified soil of about 10 mm in grain size on the 11th, 53rd, 109th, and 259th days. A compaction test was conducted on solidified crushed soil. The tests for the specimen of each age were done in a laboratory immediately after preparing the

Table 1 Basic physical properties of original soil (The Japanese Geotechnical Society, JGS)

Sample No.		1	2	
Purpose of test		physical properties/ Strength	Full-scale embankment	Standard number
Soil particle density ρ_s (g/cm^3)		2.693	2.587	JGS 0111-2009
Natural water content w_n(%)		55.97	88.6	JGS 0121-2009
Grain size characteristics	2mm-(%)	3.6	0.0	JGS 0131-2009
	75µm-2mm(%)	64.9	0.1	
	-75m(%)	31.5	99.9	
Liquid limit w_L(%)		90.5.	115.4	JGS 0141-2009
Plastic limit w_P(%)		62.0	39.4	
Ground material classification		SV	CH	JGS 0051-2009
Cone index q_c(kN/m^2)		1500	90	JGS 0716-2009
Maximum dry density ρ_{dmax} (g/cm^3)		0.961	-	JGS 0711-2009
Optimum moisture content w_{opt}(%)		51.7	-	(A-c)

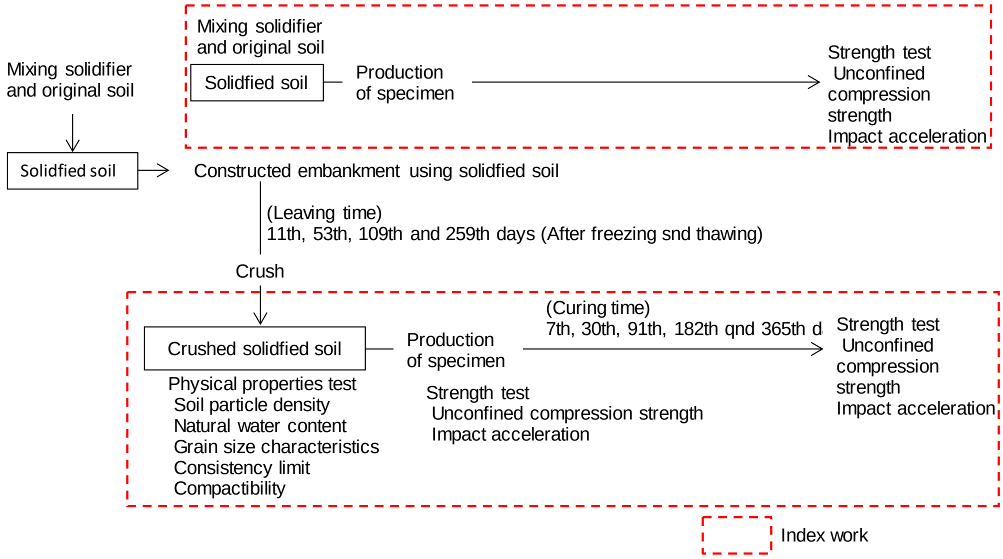

Fig. 2 Flows of the test procedures.

specimens so as to avoid further progress in the solidification of the specimens.

To clarify the time-dependent changes in the strength of the compacted crushed solidified soil specimens, the specimens for the unconfined compression test (5 cm in diameter and 10 cm in height) [5] and those for the impact acceleration test (15 cm in diameter and 12.5 cm in height) [6] were produced. The impact acceleration is measured using a steel weight with a built-in accelerometer, which was dropped in a free-fall condition. This method of measurement is applied at construction sites as a quality control technique by the Hokkaido Regional Development Bureau of the Ministry of Land, Infrastructure, Transport and Tourism.

As a result of previous studies [7], it was found that the solidified crushed soil has different compaction curves depending on the standing time and the amount of solidifying material mixed. For this reason, the density of the specimen was determined by compacting with standard proctor energy for each standing time and each amount of the solidifying material to be mixed, with reference to Cement Association's specimen manufacturing method [8]. The unconfined compressive strength and impact acceleration were measured according to the age of each specimen. Measurements were done on the day of the specimen production, i.e., on the 7th, 30th, 90th, 180th, and 365th days. Three specimens were used for the unconfined compressive strength test, and one specimen was used for the impact acceleration test. The unconfined compressive strength and the compressive strength of the solidified soil produced by mixing the original soil and the solidifier, which had a mixing ratio similar to that for the soil solidified on site, were measured using the same curing durations as those for the crushed solidified soil specimens. The flows of the test procedures are shown in Figure 2.

3.2 The Full-Scale Embankment Test

The river embankment constructed on soft ground settles after construction. Such embankment has to deform following the deformation of the ground. If the deformation of the embankment on the soft ground does not follow the deformation of the ground, gaps may be created between the embankment and the ground or cracks may occur in the embankment, which may result in water leakage. Therefore, the material of the embankment has to behave flexibly following the deformation of the

Table 2 Ground information around the full-scale embankment construction site

Soil layer symbol	Soil layer name	Thickness (m)	Ignition loss L_i(%)	water content w_n(%)
Ap1	Peat	1.4	48	414
Acp	Clay mixed with peat	1.0	26	263
Ap2	Peat	2.5	54	396
Acs	Sandy clay	2.4	-	42

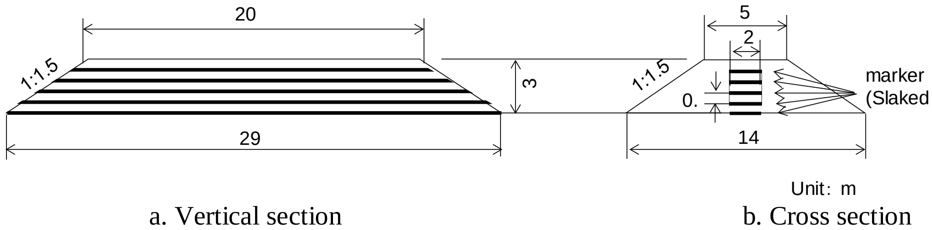

Fig. 3 Defined of term.

ground. This characteristic is also required for the crushed solidified soil when it is used as the material for an embankment on soft ground. Two full-scale embankments were constructed on soft ground using solidified soil for one embankment and crushed solidified soil for the other embankment and investigated these two embankments regarding the deformation characteristics caused by the settlement of the ground. The information on the ground around the embankments is shown in Table-2. The ground was of alternate strata of peat and clay. The water content ratios of the upper layers were high. In the past, an embankment of 2.8 m in height was constructed and found that this embankment had subsidence of 70 cm in one year.

The full-scale embankment construction test was done by constructing one embankment using the solidified soil and the other using the crushed solidified soil. The material was prepared using original soil No. 2 and a cement solidifier, which is considered as a solidifier with early strength development and a small increase in the strength development after the initial strength development (hereinafter, this solidifier will be called "ETR3"). The target strength value for the improvement of solidified soil and crushed solidified soil was a cone index of q_c = 400kN/m^2 at the construction of the embankment. The test done before the construction of the embankments were found, to obtain the target strength for the solidified soil and the crushed solidified soil, it was necessary to use 200kg/m^3 and 95kg/m^3 of ETR3, respectively. The embankment of the solidified soil was constructed during the period from September 24 to October 2, 2018, and the embankment of the crushed solidified soil with a leaving time of 28 days was constructed during the period from October 16 to 25, 2018. As shown in Figure 3, the dimensions of the embankments are 3 m in height, 20 m in length, and 5 m in crest width. The slope gradient was 1:1.5. To clarify the deformation of the embankment when it is excavated, markers were set in the embankment during the construction. For the markers, 1-cm thick lime layers with 60cm intervals in the depth direction were installed in an area of 2 m in width along the longitudinal center of the embankment. The construction machine used was a 4t-combined-roller which had a steel wheel (roller) at either of the front or the rear side and tires on the other side. Four runs of rolling compaction were done for each layer. In constructing embankments, that were worked in a short time to avoid damaging the ground. Up to the height of 1.8 m, 3 layers in one day were constructed, and after that, one layer per day was constructed. The two embankments were constructed 20 m apart between the toe ends to avoid interference from the other embankment's settlement. On August 29, 2019, which was about one year after the construction of the two embankments, the embankments were excavated in the longitudinal direction and investigated the deformation.

4. TEST RESULTS

4.1 The Physical Properties and Strength

4.1.1 Soil particle density

The specific gravity of Portland blast-furnace slag cement B is greater than that of the raw soil. Therefore, the soil particle density of the crushed solidified soil was expected to become greater with the increase in the amount of the solidifier. However, the particle density of the crushed solidified soil was only slightly greater for the greater amount of solidifier. The increase in the soil particle density with the increase in the amount of solidifier was comparatively small and considered insignificant in the calculation of the physical properties.

4.1.2 The grading characteristics

Figure 4 shows the grain size distribution curves for the crushed solidified soil with a solidifier mixing ratio of 10%. The grain size distribution curves for four specimens, excluding that for the specimen with a standing time of 259 days, are plotted on the right side of the curve for the raw soil. The grain sizes of these four specimens were greater than those of the raw soil. The similar tendency

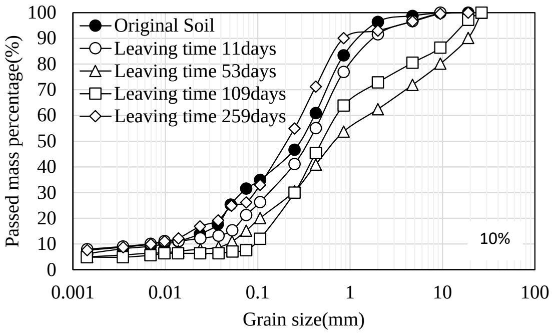

Fig. 4 Relationship between grain size and passed mass percentage

shown in Figure 4 was found in the specimens with the other amounts of solidifier. The grain size distribution test was done using specimens prepared by crushing the solidified soil using a backhoe because we simulated the actual construction work as much as possible. Because of this, it was possible that the degree of crushing of the soil specimen was not homogeneous. We consider that this inhomogeneity in crushing the specimen soil caused the unclear relationship between the grain size distribution characteristics and the standing time of the crushed solidified soil. However, it was found, in general, that the longer the standing time, the greater the grain size of the material became.

4.1.3 The consistency limits

The flow curves were obtained to clarify the consistency limit of the raw soil and that of the crushed solidified soil. The result is shown in Figure 5. The liquid limit and the plastic limit were able to be obtained only for the raw soil and the crushed solidified soil with a solidifier mixing ratio of 5% and a standing time of 11 days, 53 days and 109 days. The other specimens were non-plastic. The liquid limit became low when the solidified soil was crushed and was lower for the longer standing time, even though the curve for the 53-day specimen is below that for the 109-day specimen.

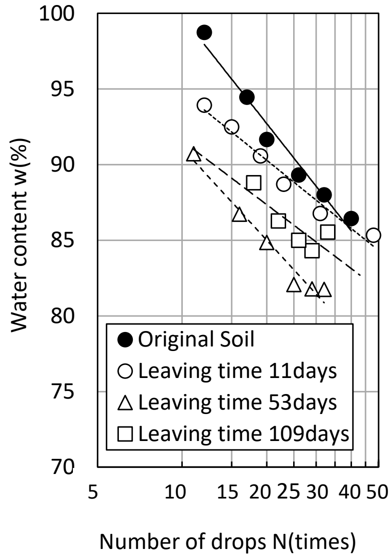

Fig. 5 Relationship between Number of drops and Water content

4.1.4 Compaction characteristics

The compaction curves for the crushed solidified soil specimens with solidifier mixing ratios of 5%, 10%, and 15% are shown in Figure 6. All the compaction curves for the crushed solidified soil specimens are above that for the original soil specimen. The maximum dry density became higher for the crushed solidified soil than that for the original soil. For the crushed solidified soil specimens with a solidifier mixing ratio of 5%, the maximum dry density changed very little with the changes in the leaving time; however, the maximum dry density changed considerably depending on the leaving time for the specimens with solidifier mixing ratios of 10% and 15%. By continue of investigation to collect more data and clarify the tendency in the changes in the maximum dry density according to the solidifier mixing ratio and the leaving time.

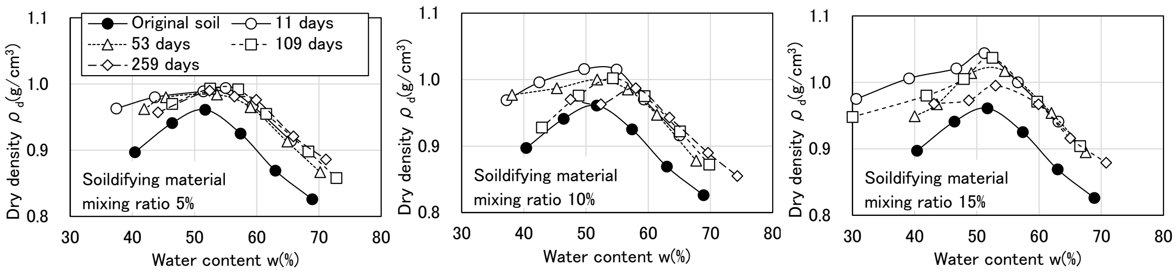

Fig. 6 Compaction curves for the crushed solidified soil.

4.1.5 The strength of the specimens immediately after production

The relationship between the leaving time and the unconfined compressive strength of the specimens immediately after production is shown in Figure 7. The relationship between the leaving time and the impact acceleration of the specimens immediately after production is shown in Figure 8. The longer the leaving time, the lower the unconfined compressive strength was. The impact acceleration was slightly higher for the longer leaving time. From this result, it was considered that the quality of the soil specimen changes from that of cohesive soil to that of sandy soil, and the quality of sandy soil became dominant with longer leaving times. The cohesion of the unconfined crushed solidified soil specimen was lower with longer leaving time, and the uniaxial compressive strength of the specimen became lower with longer leaving time. In the impact acceleration test for the confined specimen, the angle of shear resistance of the specimen became greater with longer leaving time, and the impact acceleration of the specimen became greater with longer leaving time.

4.1.6 The curing time and the strength

The relationship between the unconfined compressive strength and the curing time is shown in Figure 9. Excluding the crushed solidified soil with a solidifier mixing ratio of 5% and a leaving time of 11 days, the unconfined compressive strengths of the crushed solidified soil specimens were lower than those of the solidified soil, regardless of the solidifier mixing ratio and curing time. The unconfined compressive strength increases very slightly after the curing time of 84 days for the crushed solidified soil with the solidifier mixing ratio of 5%. However, for the specimens with the solidifier mixing ratios of 10% and 15%, the unconfined compressive strength tended to increase with the curing time. The degree of increase in the unconfined compressive strength of the crushed solidified soil for the specimen with a leaving time of 259 days was great. The increases

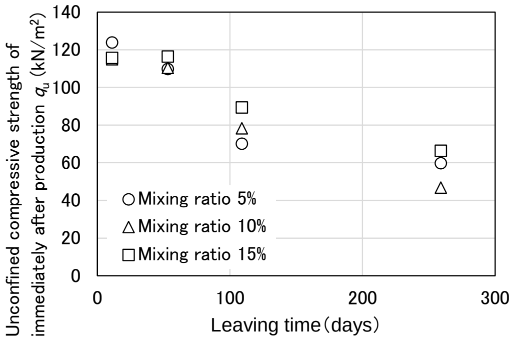

Fig. 7 Relationship between leaving time, and unconfined compressive strength of immediately after production

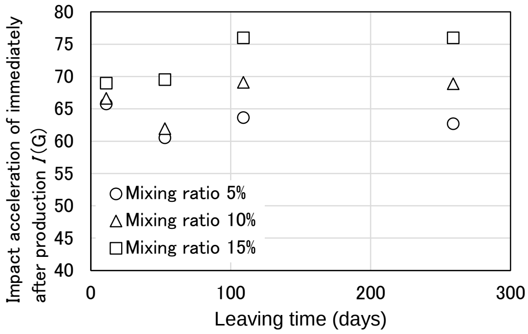

Fig. 8 Relationship between leaving time, and impact acceleration immediately after production

in the unconfined compressive strength of the crushed solidified soil specimens with longer leaving times tended to be smaller than those of the specimen with shorter leaving times. In light of this, it can be concluded that the unconfined compressive strength of the crushed solidified soil with a low solidifier mixing ratio or a long leaving time does not considerably increase. The relationship between the curing time and the impact acceleration showed a similar tendency as that observed between the curing time and the unconfined compressive strength.

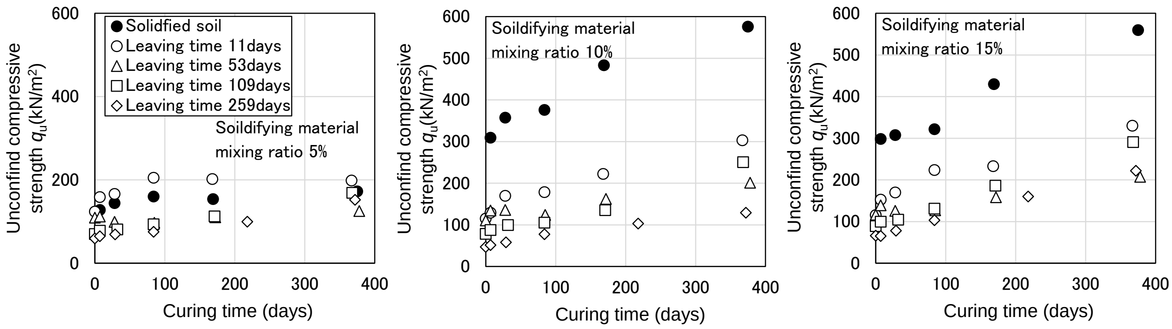

Fig. 9 Relationship between curing time and unconfined compressive strength

Photo 1 Excavation section of solidified crushed soil

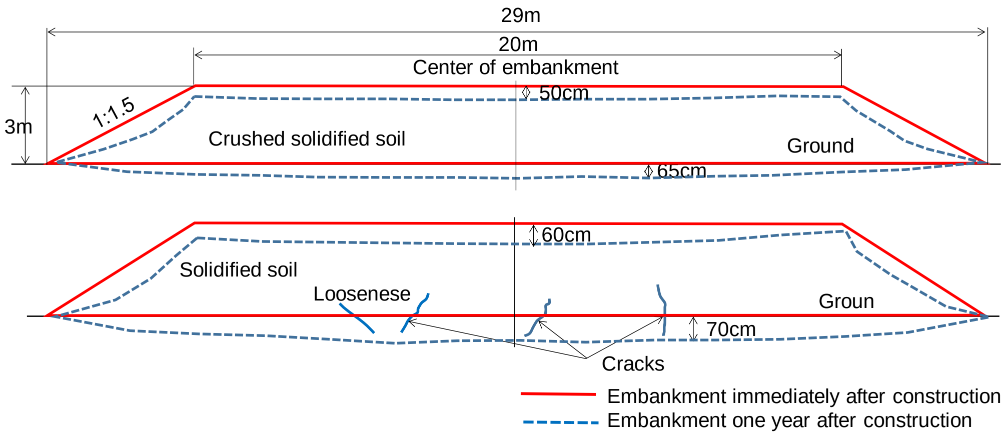

Fig. 10 Deformation of embankment.

4.2 The Full-Scale Embankment Test

Photo-1 shows the excavated cross-section of the solidified crushed soil. Also, the excavation cross-section of the embankment constructed using the crushed solidified soil is shown in Figure 10. Deformation was observed in the entire body of the embankment constructed using the solidified soil and that of the embankment constructed using the crushed solidified soil. The deformation of the embankment on soft ground is large at the center of the embankment, and it is reported that the entire embankment is deformed [9]. About 60 cm to 70 cm of settlement was seen at the center of both of the embankments. It was found that the embankment constructed using the crushed solidified soil was entirely homogeneous in soil quality and had no cracks. The embankment constructed using the solidified soil had three cracked areas and one loose area near the bottom surface. At these three locations, 2.0 m to 2.5 m long and 1 cm to 2 cm wide cracks developed upward from the bottom of the embankment were found. At the one location, the embankment toe failed from the loosening of the soil near the location of the installed settlement plate. Based on these findings, the cracks had formed in the embankment constructed using the solidified soil because the embankment was not able to follow the deformation of the soft ground were clarified; however, the embankment constructed using the crushed solidified soil followed the deformation of the soft ground similar to the embankments constructed using common soil materials.

5. SUMMARY

By using the original soil containing volcanic ash and that containing clay with a high liquid limit, the relationship between the production conditions and the physical properties and strength of the crushed solidified soil and the settlement characteristics of the embankment constructed using the crushed solidified soil on soft ground were investigated. the mix proportion and leaving time for producing crushed solidified soil which does not develop excess strength were could not determine; however, the following on the crushed solidified soil were found.

[1] The physical properties of the crushed solidified soil, including compaction characteristics, differed from those of the original soil. The compaction curves showed that the maximum dry density of the crushed solidified soil was higher than that of the original soil and that the higher the mixing ratio of the solidifier, the higher the maximum dry density became. When constructing an embankment using the crushed solidified soil, it is necessary to perform quality control by obtaining the compaction curve for each specimen.

[2] The unconfined compressive strength of the compacted crushed solidified soil immediately after the specimen preparation tended to be smaller with

longer leaving times. The impact acceleration became greater with longer leaving times; however, the increase in the impact acceleration became negligible after a certain length of leaving time. The unconfined compressive strength and the impact acceleration of the compacted crushed solidified soil increase with the curing time. The unconfined compressive strength of the crushed solidified soil with a large amount of solidifier became higher with the curing time, even for the material with the leaving time of 259 days. The strength development of the crushed solidified soil was smaller than that of the solidified soil. Excess strength development was able to be controlled.

[3] When an embankment was constructed on soft ground using the solidified soil, the embankment was not able to accommodate the deformation of the soft ground and cracks developed; however, cracks did not develop in the embankment constructed using the crushed solidified soil. The crushed solidified soil is able to be used for the material to construct embankments on soft ground was concluded.

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