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Effective use technology for crushed solidified soil - Improvement of poor soil using solidification materials -

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ABSTRACT: In light of evolving social conditions and increasing environmental conservation concerns, the effective utilization of soil materials generated at construction sites is crucial. When the generated soil is of inadequate quality, appropriate measures must be implemented to facilitate its use. One such measure involves employing stabilizing agents to produce solidified soil. However, in soil improvement using such agents, insufficient mixing time leads to low initial strength. The strength increases over time, so the final structure may become excessively strong, potentially creating difficulties during subsequent re-excavation. Additionally, reinforced soil walls require friction between the reinforcing elements and the soil material. However, solidified soil does not allow for proper friction assessment, thus limiting its use in such applications. Furthermore, embankments constructed from solidified soil on soft ground may not adequately accommodate the settlement of the underlying ground, which can result in cracking within the embankment. For river levees, such cracks can lead to water leakage and potentially to structural failure. To address these issues, crushed solidified soil—solidified soil that has been broken down after a specific period of curing—has been developed. Such soil exhibits excellent workability when it is compacted after crushing. Moreover, its relatively limited subsequent strength gain allows it to be handled as a common soil material. This paper presents case studies demonstrating the engineering characteristics of crushed solidified soil, including construction with reduced stabilizer content, its application in reinforced soil walls, and its use in river levees built on soft ground.

KEYWORDS: Crushed solidified soil, effective use, improvement, poor soil, solidification materials.

1 INTRODUCTION

When earth structures such as road embankments or river levees are constructed, the materials used are, in principle, those generated at the construction site itself or nearby sites. If the local material is suitable for embankment use in its natural state, it is used as-is. However, soil that is soft or otherwise unsuitable for embankment construction (poor-quality soil) is improved and used in the interest of resource efficiency and of extending the lifespan of disposal sites. One such method of improvement is solidification, whereby stabilizing agents such as cement or lime are mixed in to chemically harden poor-quality soil. The Geotechnical Research Team at the Civil Engineering Research Institute for Cold Region of the Public Works Research Institute has been focusing on the stable effectiveness of solidification improvement and related research. Embankment materials must be strong enough to support construction equipment during leveling and compaction and to ensure the stability of the embankment against sliding failures. Both strength requirements must be met. In solidification improvement, stabilizing agents are mixed into the soil to satisfy both (CERI 2013).

To maximize the effectiveness of solidification, construction is typically carried out immediately after the stabilizing agents are mixed into the soil. At this stage, the solidified soil is still soft because the reaction of the stabilizing agent has not progressed enough, making it difficult to level or compact the soil with construction machinery. To make the soil strong enough for immediate use, it is necessary to reduce its water content. In such cases, stabilizing agents are added not primarily to induce chemical reactions, but rather to lower the water content and improve workability. This requires large amounts of stabilizing agents. As a result, the embankment becomes excessively strong over time. In other words, to ensure sufficient strength for construction, large amounts of stabilizing agents are added, but this leads to the embankment becoming unnecessarily strong in the long term. It makes the embankment economically inefficient, and in future, if the embankment becomes unnecessary, it may be too hard to break apart easily.

Furthermore, embankments for reinforced soil walls require materials that afford friction with the reinforcing elements (Civil Engineering Research Center, 2013; 2014). Solidified soil, however, is evaluated based on cohesion with an assumed shear resistance angle of zero; therefore, it is rarely used in reinforced soil wall applications. When no suitable embankment material is available nearby, significant costs may be incurred in sourcing appropriate material.

Additionally, when embankments made of solidified soil are constructed over soft ground, the embankment may not be able to follow the ground's deformation during settlement, potentially leading to cracking. In the case of river levees, such cracks may lead to water leakage and the eventual collapse of the levee.

If solidified soil is crushed during the strength development phase, its strength gain is interrupted and further strength increases are minimized. After crushing, the soil becomes more granular and easier to work with—similar to ordinary sandy soil (granular material). Focusing on these characteristics and on the potential to reduce the amount of stabilizing agents used, we developed crushed solidified soil and have been working to address the challenges of using such soil in construction. This paper summarizes that work.

2 CRUSHED SOLIDIFIED SOIL

As shown in Figure 1, crushed solidified soil is produced by mixing a stabilizing agent into poor-quality soil, storing the mixture temporarily to allow the stabilizer to react, and then crushing the solidified mass into granular form. This turns the material into something that can be compacted like ordinary soil. After crushing and compaction, the material has a certain degree of strength and offers excellent workability. Moreover, since the strength increase over time is relatively limited, it can be treated and handled as a soil material.

Solidified soil: The product obtained by mixing a stabilizing agent into poor-quality soil.

Standby time: The temporary storage period from when the stabilizer is added to when the solidified soil is crushed.

Curing time: The time from when a test specimen (or an embankment) is created using solidified soil or crushed solidified soil to when various tests are conducted.

An example of crushed solidified soil is shown in Photo 1. Immediately after the stabilizing agent is mixed in, the resulting material is cohesive and soft, making compaction impossible. However, once it is solidified and crushed to create crushed solidified soil, it becomes dry and granular, allowing for proper

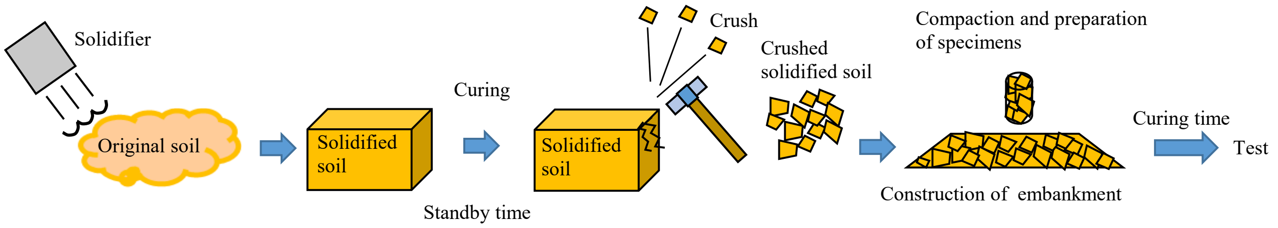


Figure 1. Flow of preparation and construction of crushed solidified soil.

(a) Crushed after solidification

(b) Immediately after mixing the stabilizing agent

Photo 1. Example of crushed solidified soil.

compaction.

3 EMBANKMENT CONSTRUCTION USING CRUSHED SOLIDIFIED SOIL

There are several examples where the engineering characteristics of crushed solidified soil were exhibited in actual construction. These include a reduction in the amount of stabilizing agent used, the use of such soil as an embankment material for reinforced soil walls, and the application of such soil in river levee construction. Each of these cases is described below.

3.1 *Reduction in the amount of stabilizing agent used (Atsuko et al. 2003)*

Peat, which is widely distributed in Hokkaido and other cold regions of Japan, was used to construct an embankment by conversion to crushed solidified soil. Peat has a high water content, so a large amount of stabilizing agent is typically required to achieve the strength required for construction as solidified soil. However, the use of crushed solidified soil allowed the amount of stabilizing agent required for improvement to be reduced.

The natural water content of the target peat was approximately 700%, making it extremely soft and unsuitable for immediate use in construction. The strengths required for embankment construction and for embankment stability were determined. That required for embankment constructability was defined as a cone index strength of 500 kN/m² - enough to support the passage of a standard bulldozer. That required for embankment stability was defined as an unconfined compressive strength of 150 kN/m² after 7-day curing. The amount of stabilizing agent needed to meet both criteria was determined. The stabilizing agent was Portland blast-furnace slag cement type B. Figure 2 shows the relationship between the standby time and the amount of stabilizing agent required to

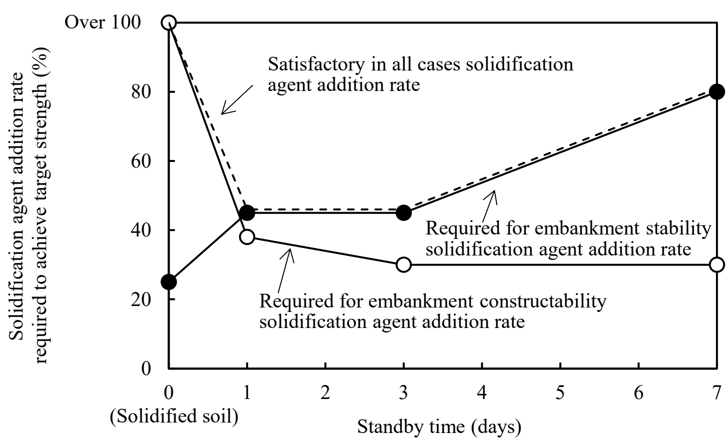
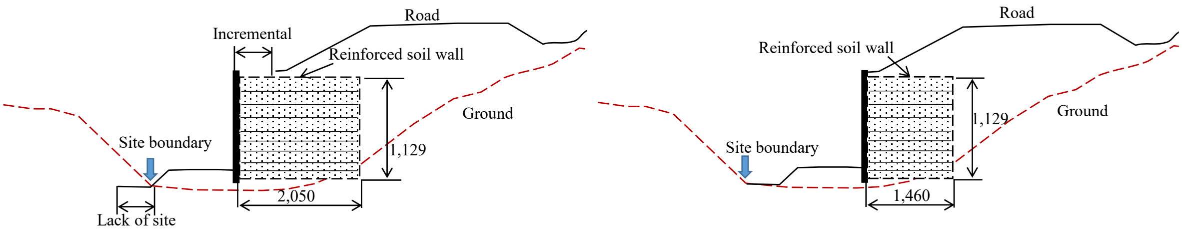


Figure 2. Standby time and the amount of stabilizing agent required to achieve the target strengths.

Photo 2. Construction of crushed solidified soil using peat as the raw material.



(a) Reinforced soil wall that can be constructed with the strength of excavated soil (b) Reinforced soil wall that can be constructed with the strength of crushed solidified soil

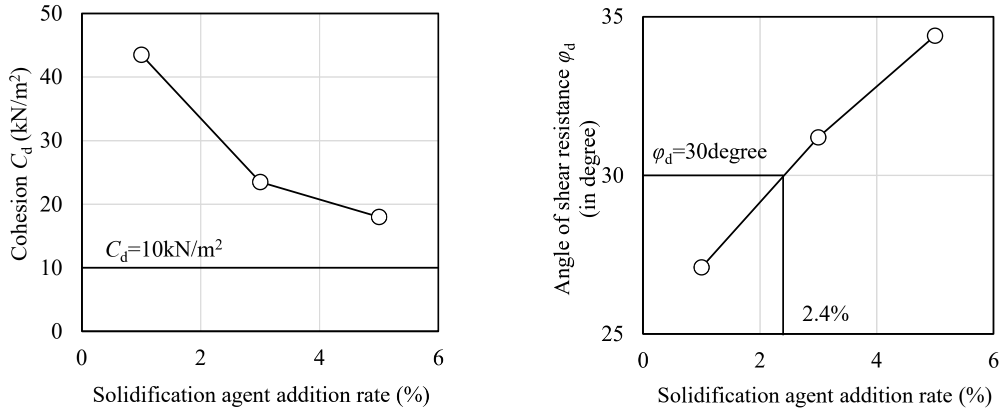
Figure 3. Overview of reinforced soil wall embankment construction.

achieve the target strengths based on laboratory tests. In the figure, the amount of stabilizer is shown as a percentage calculated as [mass of stabilizer / wet mass of peat] × 100 (%).The standby time of 0 days is that for solidified soil. Since compaction could not be performed immediately after the stabilizer was mixed in (in the case of solidified soil), specimen preparation followed the Practice for Making and Curing Stabilized Soil Specimens Without Compaction (JGS 0821-2020) for uncompactable treated soils. The strength required for construction was measured using specimens compacted immediately after mixing (for solidified soil) or crushing (for crushed solidified soil). The strength of specimens required for stability of embankments was measured after 7 days of curing.

For the solidified soil, a stabilizer content of at least 100% was needed to achieve the strength required for construction, and a content of at least 25% was needed for stability - thus, the greater value (100%) was required to satisfy both conditions. In contrast, for the crushed solidified soil with a standby time of 1 day, the stabilizer content needed to achieve the strength required for construction was only 38% and that needed to ensure stability was only 45%. Therefore, 45% was sufficient to satisfy both criteria. Converting the target peat into crushed solidified soil with a standby time of 1 day enabled the required stabilizer amount to be reduced from greater than 100% to 45%—less than half of that required for solidified soil. As shown in Photo 2, in field application, the use of crushed solidified soil allowed embankment construction with less stabilizer than the use of uncrushed solidified soil.

3.2 *Embankment material for reinforced soil walls (Atsuko et al. 2008)*

Soil material generated during the construction of the reinforced soil wall in this case had a natural water content of 16.4% and was classified as fine-grained sandy gravel (GFS). The cone index at natural water content was 985 kN/m². The angle of shear resistance (φ_d) obtained from a consolidated drained shear test was 19.5 degree, and the cohesion (C_d) was 39.4 kN/m². To achieve sufficient compaction for the embankment of the reinforced soil wall, compaction was carried out using a tire roller. A cone index of 1000 kN/m² is required for the operation of tire rollers (8 t to 20 t); however, the soil did not meet this criterion. As shown in Figure 3a), the unmodified excavated soil was not strong enough to allow a reinforced soil wall to be constructed within the site boundary. In order for the reinforced soil wall to be constructed within the site boundary, as shown in Figure 3b), the embankment material required an angle of shear resistance φ_d of 30 degree and a cohesion C_d of 10 kN/m². To achieve this required strength, the excavated soil was improved to crushed solidified soil. Based on the size of the construction yard, a curing time of 3 days was adopted. Figure 4 shows the relationship between the solidification agent addition rate ([mass of mixed stabilizer / wet mass of excavated soil] × 100) and the angle of shear resistance and that between the solidification agent addition rate and cohesion as determined by lab tests. The cohesion values satisfied the requirement for all mix ratios. The angle of shear resistance increased with increases in stabilizer content and met the target value at a 2.4% addition rate. Therefore, the required addition rate of stabilizer for embankment material in the reinforced soil wall was determined to be 2.4%. Although the quality of the embankment should ideally be evaluated based on the angle of shear resistance, direct measurement is time-consuming. Hence, for this site, embankment quality was assessed using constructability: specifically, the cone index. Based on the relationship between the angle of shear resistance



(a) Solidification agent addition rate and Cohesion (b) Solidification agent addition rate and Angle of shear resistance

Figure 4. Angle of shear resistance and cohesion of crushed solidified soil.

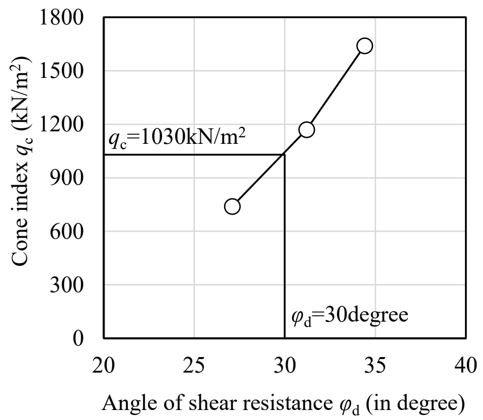


Figure 5. Angle of shear resistance and cone index of crushed solidified soil.

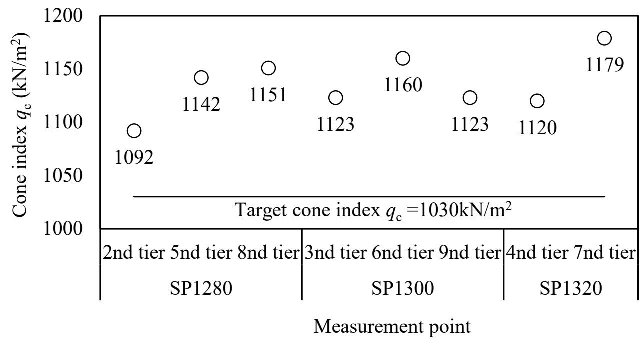


Figure 6. Cone index of embankment.

Photo 3. Construction of reinforced soil wall embankment using crushed solidified soil.

Photo 4. Reinforced earth wall constructed approximately 15 to 16 years ago

and the cone index shown in Figure 5, a cone index of 1030 kN/m² is seen to correspond to a 30degree angle of shear resistance. It was therefore determined that any soil onsite with a cone index of at least this value was acceptable. Figure 6 shows the cone index measured for the embankment. It was confirmed that all tested values exceeded the required cone index. The soil wall under construction is shown in Photo 3.

Currently, at approximately 15 to 16 years after construction, no deformation is observed (Photo 4).

3.3 *Levee embankment on soft ground (Tomoki et al. 2020; Daichi et al. 2021; Rei et al.2024)*

The Hokkaido Regional Development Bureau of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) has

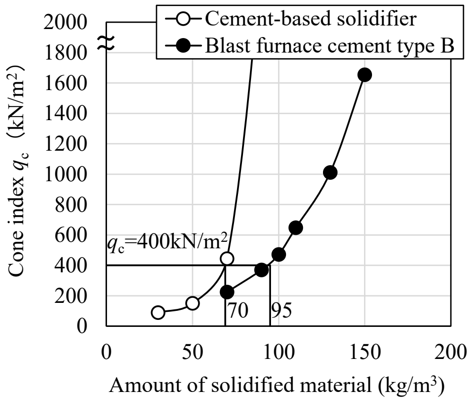


Figure 7. Amount of solidified material and cone index

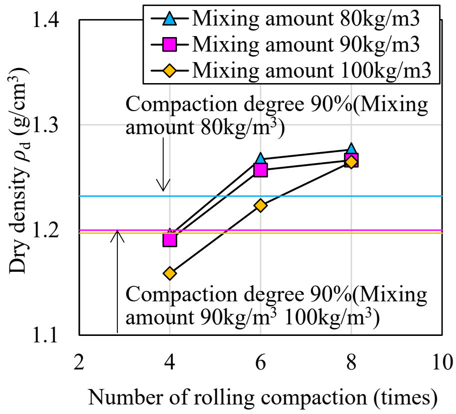


Figure 8. Number of rolling compaction and cone index.

Table 1. Permeability coefficient of crushed solidified soil.

Type of solidification material	Amount of solidified material (kg/m³)	permeability coefficient (m/s)
Blast furnace type B cement	100	7.05×10^{-9}
Cement-based solidifier	70	2.75×10^{-9}

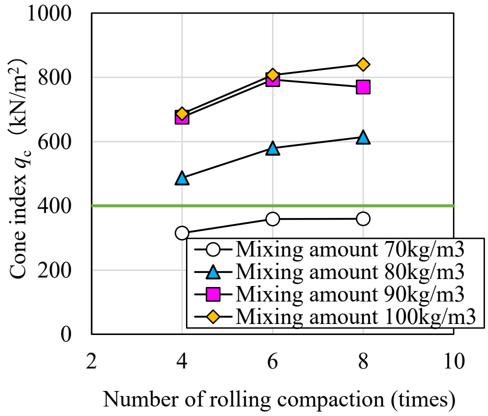
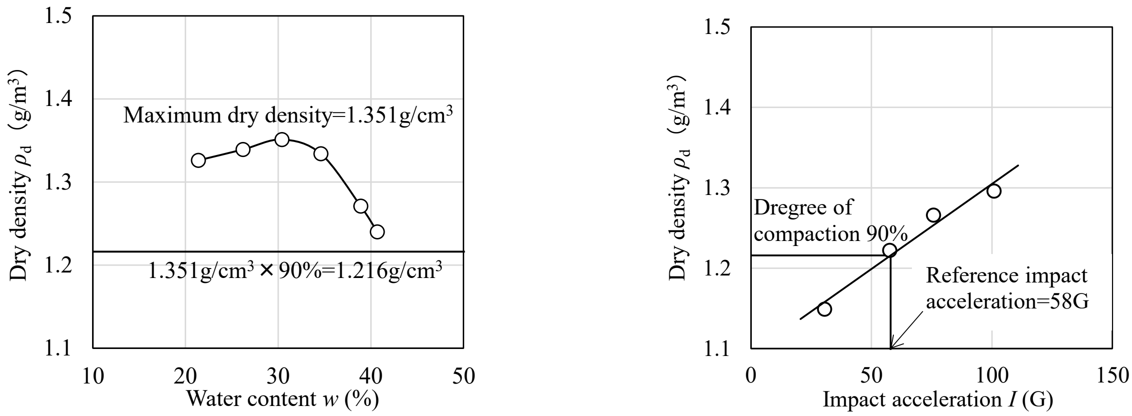


Figure 9. Number of rolling compaction and cone index.

been developing retarding basins with a combined capacity of 42 million m³ as flood control facilities for the Ishikari River (Sapporo Development and Construction Department). However, the embankments of these retarding basins are constructed on soft, peaty ground, which is extensively distributed in the area. The thickness of these peat deposits exceeds 10 meters. Crushed solidified soil has a lower degree of solidification than uncrushed solidified soil, making it a material capable of following the deformation of the underlying soft ground, similar to common soil materials. For this reason, crushed solidified soil was used for the construction of these levee embankments. In embankment construction in Hokkaido, cohesive soils are common; therefore, compaction is generally performed using low-energy methods. Specifically, 3.5-ton class combined rollers are widely used. Such construction machinery was employed for the construction of these levees from crushed solidified soil. The target improvement values for the soil were set to ensure a cone index of 400 kN/m²(sufficient for the operation of the construction machinery stated above), a compaction degree of 90%, and a permeability coefficient of 10^{-6} m/s or lower to ensure water impermeability. The standby time for the crushed solidified soil was set to 7 days based on the size of the construction yard. For embankment construction using crushed solidified soil, laboratory tests were conducted to determine the type and amount of solidifying agent required. Since the mixing, curing, and rolling compaction conditions in actual construction differ from those in laboratory tests, trial construction was carried out to finalize the amount of solidifying agent and the construction methods, including the compaction conditions. Figure 7 shows the relationship between the amount of solidifying agent [mass of stabilizer / volume of generated soil] added and the cone index obtained from lab tests. For both cement-based solidifying agent and blast furnace slag cement type B, increases in the amounts of these solidifying agents achieved higher cone index values. In this particular soil, the target cone index was achieved with a mixture of 70 kg/m³ of cement-based solidifying agent and 95 kg/m³ of blast furnace slag cement type B. The permeability coefficients under these conditions are shown in Table 1. Both mixtures provided the impermeability required for embankment structures. It was also confirmed that the hexavalent chromium leaching levels were within the regulatory limits. A cost comparison of these mixtures revealed that mixing 70 kg/m³ of cement-based solidifying agent was more economical. Subsequently, a trial compaction test was conducted using a solidifying agent mixture of 70 kg/m³ to 110 kg/m³. As shown in Figure 8, the cone index required for construction was satisfied with a solidifying agent mixture of only 80 kg/m³ or more. From the relationship between the number of compactions passes and the dry density shown in Figure 9, it was determined that six compaction passes are necessary to achieve 90% compaction.

Quality control for the embankment was performed using impact acceleration, a method (Hokkaido Development Bureau, 2025) that is adopted by the Hokkaido Regional Development Bureau of MLIT. Impact acceleration refers to the negative acceleration experienced by a weight as it comes to a stop after free-falling from a fixed height to the ground. Lower impact accelerations indicate low-density, soft ground; higher impact accelerations indicate high-density, firm ground. Thus, this value is used to estimate the density of the embankment after construction for quality control. Through lab tests, the target impact acceleration (reference impact acceleration) corresponding to the desired degree of compaction was determined in advance. During embankment construction, sections achieving impact acceleration values equal to or greater than this reference value were considered to meet the quality standards. This method is quick, simple, and easy to implement, enabling efficient quality control. Figure 10 shows the relationship between dry density and impact acceleration for



(a) Compaction curve

(b) Impact acceleration and Dry density

Figure 10. Reference impact acceleration.

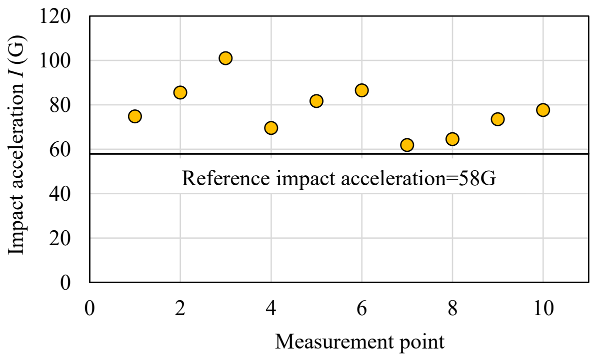


Figure 11. Impact acceleration of embankment.

specimens of crushed solidified soil mixed with 80 kg/m³ of solidifying agent. A dry density of 1.232 g/cm³ corresponds to a 90% degree of compaction, with an associated impact acceleration of 58G. Therefore, an embankment impact acceleration of 58G or higher indicates 90% compaction or more. Figure 11 shows the impact acceleration values measured for the embankment, all of which exceed the reference value.

4 CONCLUSION

As one method of effectively utilizing unsuitable soil, crushed solidified soil was developed. Taking into account the geotechnical characteristics of such soil, earth structures were constructed of such soil through three constructions: that with a reduced amount of solidifying agent, that of reinforced soil walls, and that of river levees on soft ground. It was confirmed that all embankments remained sufficiently stable after construction. Although the method involving a reduced amount of solidifying agent has only been applied in trial construction, the other methods have been widely adopted at numerous sites since the development of crushed solidified soil and are currently in use without any issues. In the future, work procedures for each construction method will be compiled into technical guidelines toward further improvements in the applicability of this technology in the field.

5 ACKNOWLEDGEMENTS

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