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Long-term properties of cement treated soil 20 years after construction

Propriétés à long terme des sols stabilisés au ciment 20 ans après construction

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ABSTRACT
Three decades have passed since the first application of the wet method of deep mixing. This paper presents results of a research on the long-term prperties of cement treated soil twenty years after construction. The long-term properties have two aspects. One is to confirm long-term strength of the cement treated soil. The other is to investigate the deterioration at the boundary surface of the treated soil. The results are that the present strength inside the treated soil mass is 2.1 times greater than 20 years ago, while at the periphery the strength reduction is observed up to a depth of 30 to 50mm from the boundary surface of treated soil.

RÉSUMÉ
Trois décennies se sont écoulées depuis le premier malaxage par voie humide des colonnes de sol traité. Ce document présente les résultats d'une recherche sur les propriétés à long terme des sols stabilisés au ciment 20 ans après construction. Les propriétés à long terme ont deux aspects : confirmer la résistance d'endurance et examiner la détérioration à la limite de la surface des sols stabilisés. Les résultats démontrent que la résistance interne actuelle de la masse de sols stabilisés est supérieure de 2,1 fois à celle d'il y a 20 ans, tandis qu'en périphérie, on observe une réduction de la résistance jusqu'à une profondeur de 30 à 50 mm depuis la surface limite des sols stabilisés.

1 INTRODUCTION

Many researches were carried out and many others are in progress to investigate mechanical characteristics of cement treated soils. In most of these studies, however, laboratory tests and field verifications were conducted on the treated soil samples aged less than a couple of years. Taking account of the life of structures, it is not sufficient test period for assurance of the long-term performance of treated soil.

So far, only several research groups have reported the long-term test results on treated soils aged more than 10 years (Terashi et al. (1992), Hayashi et al. (2001), Inagaki et al. (2001)). They tested the samples inside the in-situ treated soil and confirmed the continued strength increase with time.

On the other hand, some reports pointed out the possibility of deterioration (strength reduction) at the periphery of treated soil (Terashi et al. (1983), Saitoh (1988), Kitazume et al. (2003) and Hayashi et al. (2004)). In these studies, laboratory mixed soil specimens exposed to outer environments, such as seawater, water or untreated clay, were tested to investigate deterioration progress from the exposure surface. However, long-term change of mechanical, physical or chemical characteristic of treated soil is not entirely made clear yet.

In the present study, in-situ treated soil samples were retrieved from the treated soil block 20 years after construction and a series of test was conducted to investigate strength change with time in 20 years from construction. There are two aspects for the purpose of this study. One is to investigate the strength increase inside the treated soil block where outer environment is considered to have not affected. The other is to investigate the deterioration at the periphery of the treated soil exposed to untreated original clay ground.

2 OUTLINE OF THE TEST SITE

The test site was at the Daikoku Pier, Port of Yokohama. There are 25 berths in this pier. The foundation ground of 9 berths, called T1 ~ T9 berth, were improved by the wet method of deep mixing since 1977. This is the site where the wet method was first applied in gigantic scale by the Port and Harbor Bureau, Ministry of Transport (currently, Ministry of Land, Infrastructure and Transport). Therefore, intensive study on the cement treated soil was conducted during the construction, which is the reason the authors selected the site for investigating long-term characteristics of in-situ cement treated soil

The test site was located at the end of T2 berth. The original ground at T2 berth was thick clay layer from the sea bottom at the elevation -12 m down to -70 m where the bedrock of mudstone appeared. The layer from sea bottom to around El. -50 m was soft alluvial clay and diluvial clay was beneath it. Properties of the alluvial clay are shown in Table 1. The clay deposit may be divided into three layers according to physical properties.

The purpose of ground improvement was to improve the stability of revetment. The binder was the ordinary Portland cement and the binder content of 160 kg/m^3 was recorded in the design document. A typical cross section of T2 berth is shown in Figure 1. The ground was improved to a depth of El. -49 m as a massive block with 57 m in length and 35.9 m in thickness.

Three to six months after the ground improvement execution in 1981, a number of core samples were retrieved and physical properties, strength and calcium (Ca) content were measured. To investigate long-term characteristics, test results in 2001 in the present study were compared with those in 1981.

3 TEST PROCEDURE

In 2001, after 20 years of construction, four borings were conducted to obtain undisturbed core samples of the in-situ treated soil. The layout of the borings in cross section is shown in Figure 1. Two borings (Bor. No.1 & No.2) were inclined at angle of 20 degrees from vertical, by which continuous core samples with 80 mm in diameter were retrieved from the top to bottom of the treated soil. Other two borings (Bor. No.3 & No.4) inclined 45 degrees from vertical were conducted to retrieve the core samples with 200 mm in diameter at the side boundary

Table 1. Properties of the alluvial clay layer.

Elevation (m)	Water content (%)	Wet density (t/m³)*[1]	Unconfined compressive strength (kPa)*[2]
-12 ~ -23	80 ~100	1.50	$q_u = 5.7H$
-23 ~ -38	50 ~ 60	1.68	$q_u = 8.6 + 4.9H$
-38 ~ -50	75 ~ 85	1.53	$q_u = 64.7 + 2.7H$

*[1] Average value, *[2] H = 0 at El. -12 m

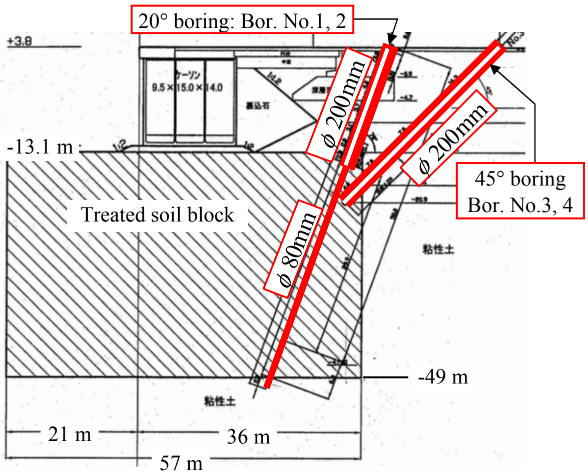

Figure 1. Cross section of the improved ground and borings.

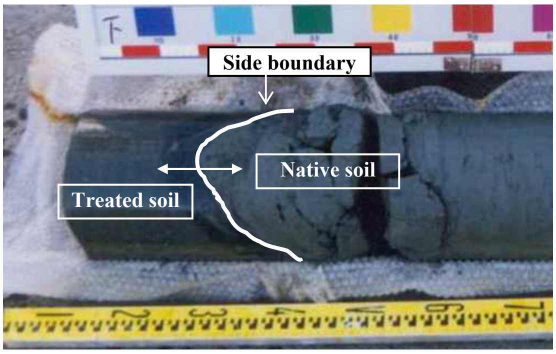

Photo 1. The core sample of Bor.No.3 at the side boundary.

between treated soil block and original ground. Photo 1 shows the core sample containing the side boundary at a depth of about El. -18 m.

The core samples taken by Bor. No1 and No.2 were tested to determine the water content, wet density and unconfined compressive strength of treated soil inside the treated soil block to which outer environmental condition had negligible influence.

The core samples by Bor. No.3 and No.4 were tested to examine whether deterioration had occurred or not at the periphery of the treated soil block exposed to the native clay. Total Ca content in soil was measured on the treated and the native soils by atomic adsorption spectrometry. Strength was measured by means of the needle penetration test to investigate the strength distribution in detail. In this test, a sewing needle with a diameter of 0.84 mm was penetrated into the treated soil sample at a constant speed of 3 mm/min. Pore size distribution of the treated soil was measured by Mercury Intrusion Porosimetry (MIP) to investigate the relation between the change of microscopic structure and the deterioration.

To estimate the relationship between penetration resistance and unconfined compressive strength q_u, the needle penetration tests were conducted on several specimens of Bor. No. 1 and 2 before unconfined compression tests. The penetration resistance at penetration depth of 5 mm, Q_N, was correlated to q_u. as q_u (kPa) = 76.4Q_N (N).

4 LONG-TERM PROPERTIES INSIDE THE TREATED SOIL BLOCK

Figure 2 compares the water content and wet density distributions with depth between 1981 (open triangles) and 2001 (solid circles). These physical properties have not changed in the last 20 years. The distributions with depth could be divided into three layers of upper, intermediate and lower layer, which reflected the native soil profile as shown earlier in Table 1.

The strength distributions with depth are compared between 1981 and 2001 in Figure 3. The strength in 1981, 93 days after construction, was based on check borings which were conducted near the present Bor. No.1 and 2. In 1981, the average field strength throughout the depth was 6.3 MPa in terms of unconfined compressive strength. After 20 years in 2001, the average field strength was 13.2 MPa. About 2.1 times strength increase was observed in these 20 years although no change was found in the physical properties.

The strength at the test site is plotted versus logarithm time in Figure 4. On the basis of physical property shown in Figure 2, the treated soil can be divided into three layers, upper layer from El. –13.1 m to -24 m, intermediate layer from -24 m to -37 m, lower layer from -37 m to -49 m. The strength increase is shown for each layer. In Figure 4, similar research results on long-term strength increase are plotted together. The summary of the previous researches referred is shown in Table 2. Although various binders and improvement patterns were used, the strength of treated soil indicated steady increase up to more than 10 years. As regarding this test site, the rate of strength increase from 93 days to 20 years was 1.6 times for upper layer, 2.1 times for intermediate layer, 2.6 times for lower layer. The overall average of these for the present study was around 2.1.

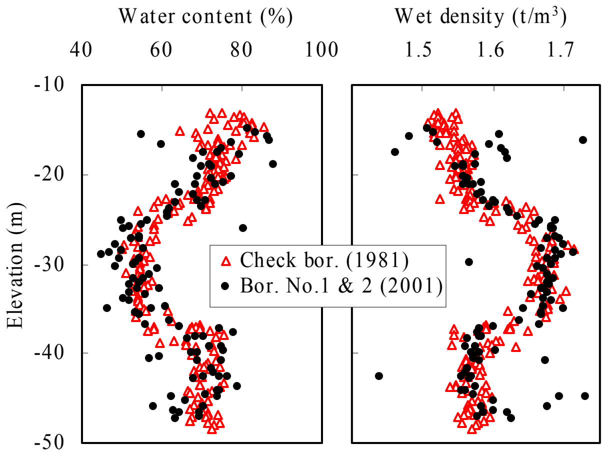

Figure 2. Physical properties distributions with elevation.

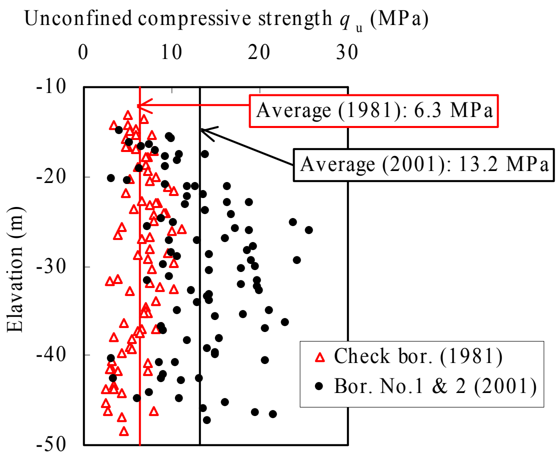

Figure 3. Strength distributions with elevation.

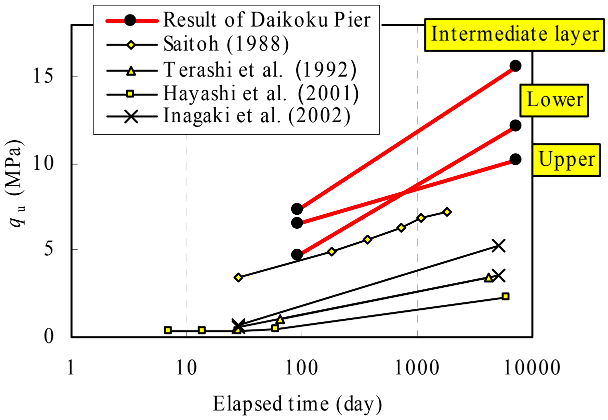

Figure 4. Long-term strength increase with time.

Table 2. Summary of researches on long-term strength.

Research	Original soil	Binder	Treatment pattern / site
This research	Clay	OPC	Block / in situ
Saitoh	Clay	OPC	In mold / laboratory
Terashi et al.	Clay	Lime	Column / in situ
Hayashi et al.	Clay	BSC	Column / in situ
Inagaki et al.	Peat and clay	SC	Tangent column / in situ

OPC: Ordinary Portland cement
BSC: Blast Furnace Slag cement type B
SC: Special cement-type hardening agent

5 DETERIORATION AT THE PERIPHERY OF THE TREATED SOIL BLOCK

The upper and lower half of Figure 5 respectively shows strength and Ca content distribution at the periphery of the treated soil retrieved from Bor. No. 3 and 4. Horizontal axis indicates the distance (depth) from the boundary surface in logarithmic scale. The distance zero means the boundary surface.

The strength in terms of q_u shown either by solid or open circle was estimated by the needle penetration test results. The line shown as "average of inside" indicates the average value of unconfined compressive strength measured on the core samples inside the treated soil at the upper layer from El. -13.1 m to -24 m retrieved from Bor. No.1 & 2. The strengths at depths more than 30 - 50 mm coincided with the average inside the treated soil. This portion was regarded as the sound area. At the area from the boundary surface to a depth of 30 - 50 mm, the strength was confirmed to be lower than that of the sound area and decreased toward the periphery. The portion indicating the strength reduction was considered as the deteriorated area.

The circles in the lower half of Figure 5 show the Ca content distribution measured in 2001 on samples from Bor. No. 3 and 4. The distributions showed the clear reduction at a depth between 30 to 50 mm. The line shown as "average of inside" shows the average value of Ca content measured in 1981 at the equivalent depths. Ca content in the sound area was equal to that measured 20 years ago. In the deteriorated area, Ca content decreased toward the periphery except at depths of 5 - 10 mm. The overall pattern of Ca content distribution was in good agreement with strength distribution. The close correlation was suggested between the deterioration and Ca content reduction. The exception in the overall trend at a depth of 5 - 10 mm will be discussed later.

Figure 6 shows Ca content distribution across the boundary between treated and native soil at Bor. No.3. Ca content in the treated soil decreased toward the periphery of treated soil. In contrast, Ca content in the original ground increased toward the periphery. It is evident that Ca leaching phenomenon from treated soil to native soil occurred at the boundary due to the concentration gradient of Ca^{2+} between treated and native soils.

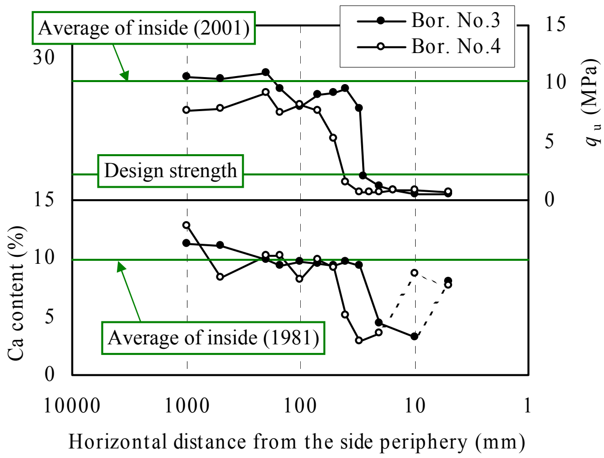

Figure 5. Comparison of strength and Ca content distribution.

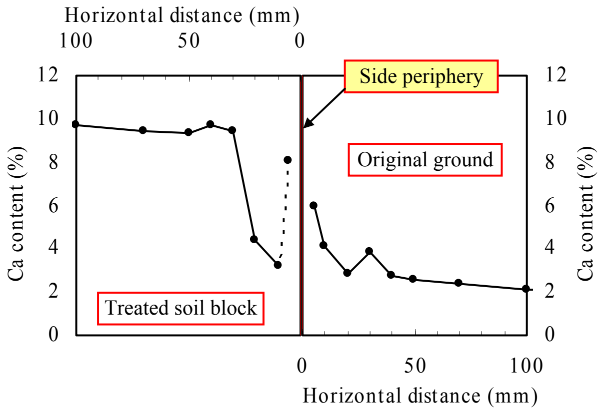

Figure 6. Ca content distribution across the boundary.

The phenomenon might be one of the major factors that caused the deterioration of treated soil.

To investigate the mechanism of the deterioration from the viewpoint of the microscopic structure, the pore size distribution was measured by MIP. Figure 7 shows pore size distributions of the treated soil taken by Bor. No.4. The samples at depths of 5, 10 and 30 mm were retrieved from the deteriorated part of the treated soil. The samples at depths more than 50 mm were from the sound part. The peak values of pore size distributions of the deteriorated area were 10 times larger than those of the sound area. The pores smaller than 0.1μm were expanded and the volume of the pore with the diameter d, 0.1μm < d < 1μm, increased during the process of deterioration. The change of the porous structure of the treated soil might have resulted in the strength reduction. The expansion of pore size was thought to be caused by the dissolution of cement hydration products, such as calcium silicate hydrate and calcium hydroxide. The dissolution in turn might be due to the leaching and decrease of the Ca^{2+} concentration in the pore water of the treated soil.

In Figures 5 & 6, exceptional Ca concentration was found at the close vicinity of the boundary within the area of strength reduction The similar results were found in laboratory tests reported by Saitoh (1988), Kitazume et al. (2003) and Hayashi et al. (2004). In order to investigate re-increase of Ca content, the type of calcium compound was examined by X-ray diffraction analysis. Figure 8 shows the X-ray diffraction patterns from treated and native soils. Only the treated soil samples at a depth of 0-10 and 10-30 mm has the clear peak of calcium carbonate ($CaCO_3$). At the area close to the surface exposed to the outer environment, calcium cations seemed to be fixed as $CaCO_3$ which did not contribute to the strength of treated soil.

In order to estimate the rate of deterioration with time, authors conducted laboratory tests termed "exposure test" in which the laboratory mixed specimens made by native soil at Daikoku Pier were exposed to different environments such as seawater, water and native soil (Ikegami et al. (2004)). The depth of deterioration with time obtained by the lab. test results are shown in Figure 9. In the figure, the field data at Daikoku Pier and the results of the similar researches by Terashi et al. (1983), Saitoh(1988), Kitazume et al.(2003) and Hayashi et al. (2004) are plotted together. The strengths q_{u28} shown as references are the strength of the treated soil specimen after 28 days curing under sealed condition. The progress of deterioration depth in logarithm scale was almost linear to logarithm time, and the slopes in all the test cases were about 1/2 irrespective of the strength of specimens and the exposure conditions. The rate of deterioration was proportional to a square root of time. The same relation between the depth of deterioration and time was also obtained by a numerical simulation proposed by Nishida et al. (2003) that assumed ions migration primarily based on the diffusion by Ca concentration gradient. Judging from the results of laboratory tests and the numerical analysis, it may be possible to predict long-term deterioration by extrapolation of the short-term result of the exposure test assuming the deterioration progress is in proportion to a square root of time.

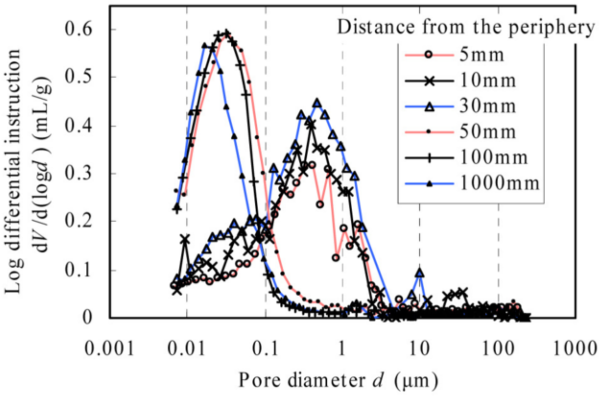

Figure 7. Pore size distributions of the treated soil.

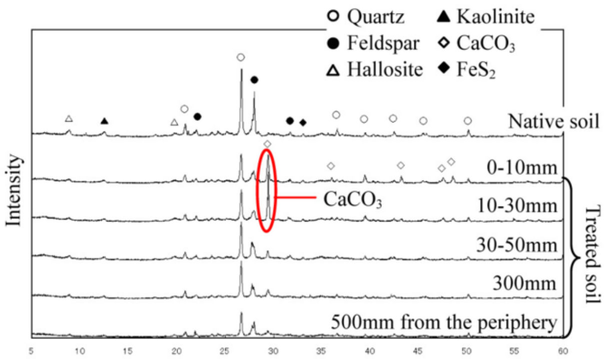

Figure 8. X-ray diffraction patterns from treated and native soil.

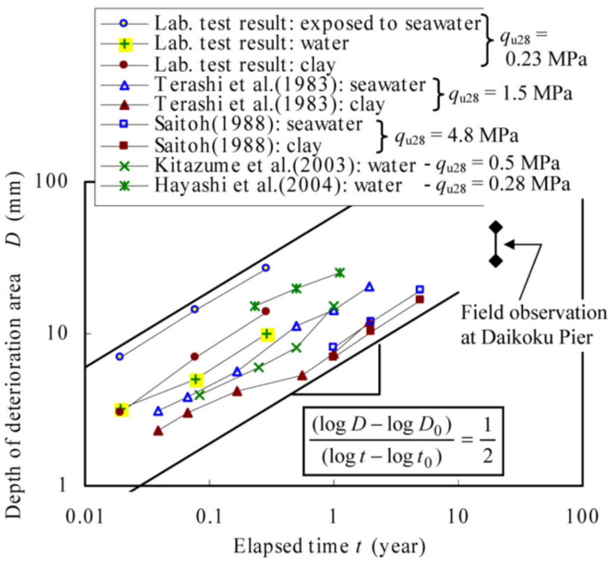

Figure 9. Progress of the deterioration area with time.

6 CONCLUSIONS

The long-term property change of treated soil has two aspects. One is the strength increase with time and the other is the deterioration such as the strength reduction at the boundary surface of the treated soil. To investigate these aspects a series of test was conducted on the treated soil samples retrieved from the improved ground aged 20 years. The conclusions are;

1) No change in the water content and wet density was detected in the treated soil block where outer environment is considered to have not affected.
2) The strength inside the treated soil block increases with time up to 20 years. The similar strength increase up to 10 years were reported in literature..
3) At the boundary of treated soil block, strength reduction and Ca leaching are confirmed. The deterioration in the past 20 years is around 30 to 50 mm at Daikoku Pier.
4) There is a possibility that Ca leaching from treated soil is one of the major factors that caused the deterioration.
5) Strength reduction is considered to be associated with expansion of pore size of treated soil due to the dissolution of cement hydration products.
6) The deterioration progress is in almost proportion to a square root of time.

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