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Densification/compression by compaction of a granular geomaterial changed by crushing dewatered sludge with air

Densification par compactage de géomatériau modifié par bombardement des boues égouttées avec de l'air

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ABSTRACT
To improve the construction surplus soil and to use the soil as a geomaterial, a densification technology of soil with high water content such as dewatered sludge is studied. The densification is brought by the change from the 'consolidation material' like clay to the 'compactable material' like sand. The soil is crushed with air to an assembly of clay pebbles, the water content of which is ease to decrease, and therefore the assembly can be compacted to high density without long consolidation time. The soil became low compressible and had high shear resistance, which can be describe by Super/subloading Yield Surface model.

RÉSUMÉ
Etude des technologies de densification des sols à haute teneur en eau du type boues égouttées dans l'objectif d'améliorer les déblais de construction pour leur utilisation sous forme de géomatériau. La densification est obtenue par passage d'un "matériau de consolidation" comme l'argile à un "matériau compactable" comme le sable. Le sol est bombardé avec de l'air jusqu'à transformation en gravillons d'argile dont la teneur en eau peut facilement être réduite ce qui permet un compactage en haute densité sans perte de temps d'attente de consolidation. Le sol devient faiblement compressible et présente une résistance au cisaillement élevée que l'on peut décrire à l'aide d'un modèle de contrainte des surfaces en super/souschargement.

1 INTRODUCTION

Compared with other kinds of retrieved construction soil, clay sludge recovered from dredging or excavating by shield tunneling method has always been difficult to reuse as a foundation material because of its high water content. A current major challenge in foundation engineering is how to densify and improve this type of material for effective recycling.

There have been many accounts of (1) **improvements in principle**, i.e. the **"chemical"** and **"mechanical"** mechanisms required before renewed materials can be put to use in foundation work. Further, it is equally important that (2) **"guaranteed quality" standards for new materials**, i.e. statements of requisite mechanical properties, should be expressed and formulated in geotechnical terms. Both sets of conditions are indispensable if a materials renewal technology is to be adequate and effective for the needs of recycling. The research reported here concerns a **non-chemical** crushing, aeration and compaction technology for the enhanced densification of "dewatered" cake (hereafter called "unprocessed soil"), as prepared from dredged sludge with the use of a filter press. The aim will be to explain the results of a basic experiment, in line with criteria (1) and (2) above, and then to specify the conditions for the most adequate and effective mode of future use. If a rapid bulk method of densification for saturated clay with high water content can be achieved in this way, then even apart from the problem of disposing of dredging spoil, the benefits will be considerable.

Even if dredged clay in its initial consolidated form of "dewatered cake" can be regarded as dewatered to some extent, its actual water content still remains high, making it hard to work with in bulk. To densify it, and make it easier to handle, calls for a **conversion**, in theoretical geomechanical terms, **from "consolidation" to "compaction."** That is to say, the clay, as initially consolidated through simple prolonged pressing, is crushed and aerated so as to turn it into a compactable granular material like sand; then, once the drying process has been assisted by the proportional increase in surface area, it is densified once more through a final rapid compaction. After subsequent saturation, the material reverts to a heavily overconsolidated unstructured clay. If quicklime is also added at the crushing and aeration stage of the process, a dramatic improvement is achieved in the densification effect and in the quality of the finished product. But as this would stray into **chemistry**, the relevant data are all excluded from the present paper.

2 CHAIN ROTARY CRUSHER-MIXER AND ITS PULVERIZING AND HOMOGENIZING FUNCTIONS

To convert dewatered sludge cake into a granular material, a chain rotary crusher-mixer was used (Ninomiya et al., 2002, hereafter: "crusher-mixer"). A schematic diagram can be seen in Fig. 1. The center of the mixing chamber (diameter 500mm, height 700mm) is occupied by a rotary shaft armed with 3 banks of 4 chains each, for a total of 12 chains in all. The operation of the motor sets the chains rotating at high speed in a horizontal orbit, generating a percussive force that pulverizes the soil material fed in from the hopper, which, after being homogeneously mixed with any additives used, is finally discharged through a chute. The rotation speed of the chains varies from 0rpm to 900rpm, and is freely adjustable to control the percussive force for the material to be pulverized. The present research made no use of additives, however; the purpose was simply to crush the soil and mix it with air in order to turn the dewatered cake into an aggregate of clay granules in a non-saturated state (henceforth: "processed soil"). The machine employed was an experimental model, with dimensions of between 1/2 and 1/3 of what would be encountered in practice.

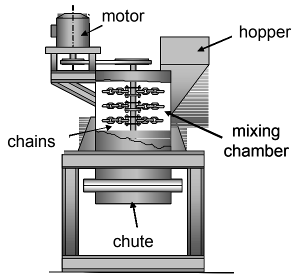

Figure 1. Chain rotary crusher-mixer.

3 CHARACTERISTIC DIFFERENCES BETWEEN SAND AND CLAY

As our suggested procedure of enhanced densification involves the "turning of clay into sand," we need to say something now about the differences between sand and clay, particularly with respect to their compressive properties. Naturally, sand corresponds to a processed soil, and clay to an unprocessed one. The compressive properties of sand include its compaction behavior, and its manner of rapid consolidation when subjected to repeated small shear forces, such as occur using a rammer. In contrast, clay exhibits properties of consolidation, and can tolerate long periods of compression due to progressive consolidation under conditions of heavy loading. While these are reasons enough for calling sand a compacting and clay a consolidating material, we should also note that the densification of clay requires a good deal of force and time, whereas the densification of sand can be induced rapidly and with little expenditure of force.

These differences in behavior between sand and clay can be accounted for theoretically using the elasto-plastic constitutive SYS (Super/subloading Yield Surface) Cam-clay model proposed by Asaoka et al. (2000, 2002). For details the reader is referred to the References, but as far as the responses to plastic deformation are concerned the basic point is that in clay the loss of overconsolidation proceeds faster than the decay in structure, whereas in sand it is the breakdown in structure which is rapid. Regarding structure, the difference in the relation of a soil's void ratio and bulk to its compression curve, comparing a naturally deposited clay on the one hand with a remolded clay on the other (Fig. 2), is expressed in the model by a structure index $1/R^*$ (the greater the value of $1/R^*$, the higher the degree of structure). By changing how to evolve structure and overconsolidation in this way, it becomes possible to distinguish between sand and clay and account for the differences in their mechanical responses. As one example of a calculation using the SYS Cam-clay model, let us focus on the compressive properties of sand by comparing its compressive behaviors under a repeated shear force in drained conditions and under a monotonous isotropic compression load.

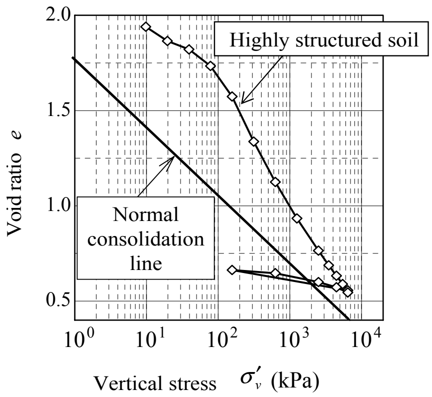

Figure 2. One-dimensional compressive behavior of structured clay.

Let us assume the material constants of the sand to be as given in Table 1. In Fig. 3 we see the calculated result of a drained triaxial compression and extension test in which this sand, in its extremely loose initial state (normally consolidated and highly structured), is subjected at constant lateral pressure to a repeated shear force q of 60kPa. Even at this small level of repeated force the breakdown in the soil structure is rapid, and leads to a considerable amount of compression. After compression the sand is left in an extremely dense state, represented in the model as overconsolidation with a low degree of structure. Also shown in the same figure is the result for the monotonous isotropic loading test. Here, even at over 2000kPa, compression has not progressed as far as the void ratio after 5 cycles in the drained triaxial compression and extension test, and, as the calculation is able to indicate, the sand is in a compacting rather than a consolidating material.

Clay, in contrast, is a consolidating material, and for reasons of low permeability alone it is clear that no compaction, or densification in response to repeated drained shearing, can be expected from it. In section 6 below, on the basis of a test, we shall be seeing in addition that the compaction of clay has no effect on compression. On this evidence, too, we shall be able to show that clay is a consolidating material, and not a compacting one.

Table 1. Material constants and initial conditions of the loose sand at point A in Figure 3.

Elasto-plastic parameters		Evolution parameters		Initial conditions	
M	1.00	m	0.08	p'_0	294 kPa
N	0.97	a (b,c)	2.3(1.0,1.0)	v_0	1.92
$\tilde{\lambda}$	0.05	b_r	200.0	$1/R_0$	1.0
$\tilde{\kappa}$	0.012	m_b	0.7	$1/R^*_0$	100.0

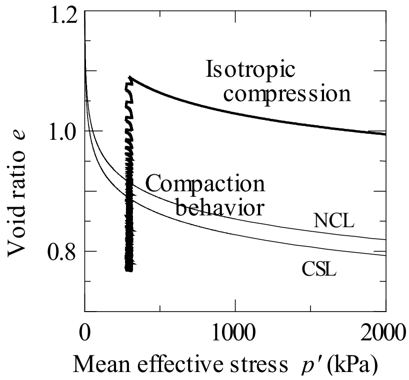

Figure 3. Compaction and isotropic compression behaviors of sand.

4 PHYSICAL PROPERTIES OF THE CLAY TEST SAMPLE (DEWATERED CAKE) AND EXPERIMENTAL PROCEDURE

The physical properties of the dewatered cake (untreated soil) used in the test are set out in Table 2. The source soil, retrieved from construction work and from dredging, was first turned into a slurry form, and then pressed over a short span of time. The dewatered cake obtained through this process is a densified but unconsolidated clay soil, which cannot be used as a foundation material in its untreated state.

Table 2. Physical properties of dewatered cake.

Initial water content w (%)	39.7
Specific gravity G_s	2.71
Liquid limit w_L	52.0
Plastic limit w_P	28.8
Plastic index I_P	23.2

5 GRAIN SIZE DISTRIBUTION OF TREATED SOIL AND EASE OF DRYING

Investigations were conducted to ascertain the grain size distribution of the treated soil discharged from the crusher-mixer, and the ease of drying this soil in relation to the increase of surface area to volume. A decrease in water content means a greater densification of the treated soil after compaction.

5.1 *Change in grain size distribution before and after soil treatment*

If the treated (pulverized and aerated) soil is sufficiently dried it preserves the granular state acquired in the treatment, allowing grain size distribution to be analyzed. A grain size distribution of this sort is shown in Fig. 4. The treated soil is represented as assembly of granular mateial, and the grain size distribution curve shows a smooth rise. The greater the rotation rate of the chains, the smaller the overall grain size. For a set rotation rate of 600rpm, if soil which has been once through the crusher-mixer (1×600 treatment) is sent through a second time (2×600), the grain size is found to be smaller and the distribution more even. But for soil sent through a third time (3×600) the grain size distribution curve barely diverges any further, so that for the dewatered cake used in the present test it seems that a third crushing or more brings no more change in grain diameter size.

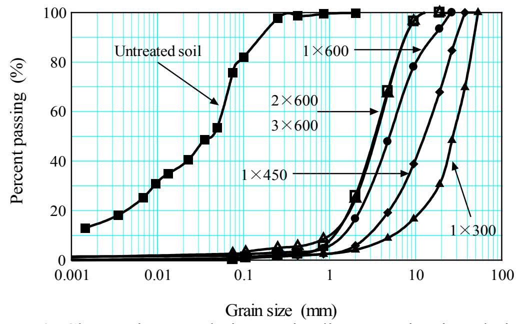

Figure 4. Change in cumulative grain diameter size in relation to differences in crushing and mixing treatment.

5.2 *Difference between treated and untreated soil regarding change in water content against time*

Figure 5 shows the differential changes in water content against time that appeared in samples (approx. 25g each) of soils in various degrees of treatment placed in Petri dishes and left with a constant temperature. Treated soils shed water at more than double the rate of the untreated sample. Also, for the same crusher setting of 600rpm, the reduction in reduction content was found to remain the same for samples treated more than twice. This agrees with the finding for grain size distribution in subsection 5.1. In other words, the rate of change in the water content is influenced by the difference in grain size distribution curve.

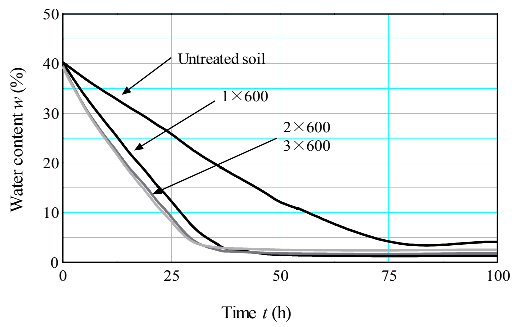

Figure 5. Differences in ease of drying between treated and untreated soils.

6 DENSIFICATION OF TREATED SOIL THROUGH COMPACTION AND MECHANICAL PROPERTIES AFTER COMPACTION

6.1 *Changes in compaction behavior between untreated (consolidating) and treated (compacting) soils*

Figure 6 shows the results of a test in which treated soil was compacted by rammer. In the case of larger-grained soils, either untreated altogether or crushed at the lower rev rate of 300rpm, while the dry density shows ups and downs. These being clay soils, no densification can be achieved through compaction. On the other hand, in the fully treated soil compaction becomes possible depending on the state of progress in the drying. While there is a certain undeniable breadth to the compaction curve, it is possible to find a maximum dry density and optimum water content. The test does therefore show how an initially consolidating material (untreated soil) is converted into a compacting one through crushing and aeration. However, at the stage immediately after processing (water content approx. 40%), since even in the treated soil there is no change in the water content of the soil grains themselves, compaction cannot yet occur and the drying rate is consequently no different from that of untreated soil. What can be said, then, is that in the treated soil, with its smoother grain size distribution curve, the individual grains dry out more readily and then, once the optimum water content is attained, there is an enhancement of the compaction effect.

Figure 7 shows results of a compaction test, in which the number of compaction by rammer (and hence the compaction energy) was varied. After drying the treated soil to the optimum water content, it was compacted with a varying number of blows. While the treated soil was found to reach maximum dry density upon a small number of compactions (around 30 times), a much larger number was required before the untreated soil could be rammed into a similarly dense state. From this evidence, once more, it is clear that while the untreated soil is consolidating in its behavior, the treated soil is compacting.

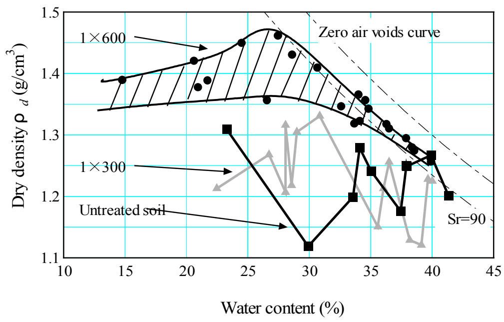

Figure 6. Conversion from a consolidating into a compacting material.

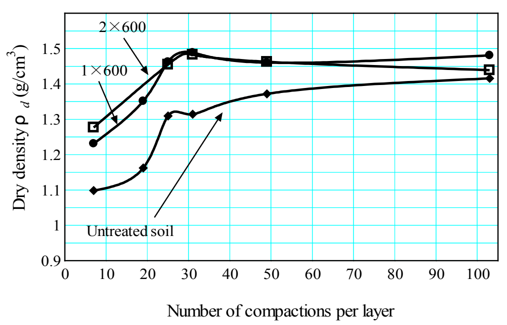

Figure 7. Relation between dry density and number of compactions, in treated and untreated soils.

6.2 *Densification of treated soil through compaction and subsequent mechanical properties*

Figure 8 shows the compaction curve for a treated soil (1 x 600), with an optimum dry density specific volume v (= 1 + e; e : void ratio) of 1.85, compared with the result of the oedometer test for untreated soil. Prior to compaction, the treated soil is in the state of a loosely packed particulate media having a specific volume of approximately 3 for the specimen as a whole. Upon compaction, a rapid densification occurs, bringing the specific volume down to 1.85. For an untreated soil, on the other hand, it has proved impossible to bring the specific volume down to 1.85 by means of compaction. Judging from the compression curve in the figure for untreated soil, the only way of achieving this would be through long-term consolidation at a vertical stress force of 1000kPa, the level corresponding to specific volume v = 1.85. Yet simply by converting the soil from consolidating to compacting material status, large-scale densification can be achieved with a much smaller loading, and in a very short time.

Also shown in Fig. 8 is the one-dimensional consolidation behavior of a treated soil after compaction. As long as compaction continues the behavior is no different from that of sand, but afterward it changes to resemble the behavior of de-structured overconsolidated clay. Moreover, after compaction hardly any swelling or subsidence is observed even when the soil is subjected to a small vertical load of 39kPa and steeped in water.

This is essentially a case of unsaturated soil compaction, but a ‘compaction’ calculation was performed in which a treated clay soil, as a granular aggregate material, was assumed to be subjected to the same kind of drained one-dimensional repeated loading that might normally be applied on a saturated soil. The elasto-plastic parameters are found through a mechanical testing of the remolded dewatered cake, and the initial conditions are taken as representing treated soil in a loosely packed state. The evolution parameters are determined with reference to the typical parameters of sand (see Table 3). As seen in Fig. 9, the crushed and aerated mixture of treated soil behaves as a loose granular body of high specific volume, and shows considerable densification after some 20 cycles of repeated drained loading. The soil structure is almost completely lost in this process, leaving an overconsolidated soil. This result agrees with what can be found from experiments.

This is a calculation based on analogy, but it does show that compaction behavior and its effects are open to description through numerical analysis. It is fair to suppose that the SYS model will have a large role to play in assuring “guaranteed quality” – one of the principles for the future improvement of materials.

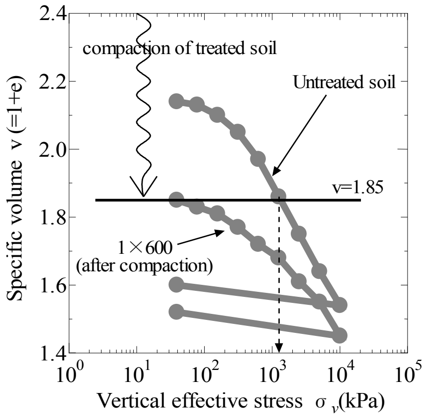

Figure 8. Compaction and compression curve.

Table 3. Material constants and initial conditions of the treated soil.

Elasto-plastic parameters		Evolution parameters		Initial conditions	
M	1.50	*m*	0.2	σ'_v	39.2kPa
N	1.98	*a* (*b*,*c*)	1.10(1.0,1.0)	v_0	2.54
$\tilde{\lambda}$	0.11	b_r	0.0	$1/R_0$	1.0
$\tilde{\kappa}$	0.011	m_b	0.0	$1/R^*_0$	100

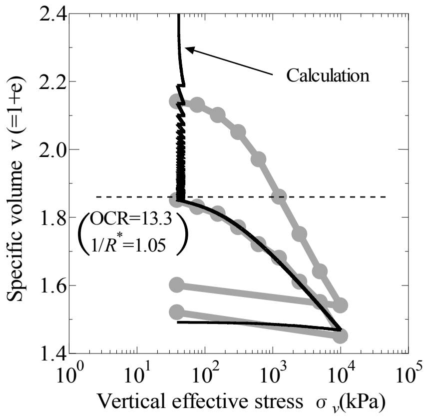

Figure 9 Calculation result of the treated soil.

7 CONCLUSIONS

Experimental research into the densification of dewatered clay cake led to the following findings.

1) By crushing and aeration dewatered cake can be converted into a granular aggregate body. If the overall grain size in this body is small and the grain size distribution curve is smooth, the proportional surface area will also increase, leading to greater ease of drying and thus to a more rapid decrease in water content. Under the conditions assumed in this research, the granular aggregate body (“treated soil”) is found to shed water at more than double the rate of the original dewatered cake (“untreated soil”).
2) This makes it feasible for the granular treated soil to be compacted. If this is performed at the optimum water content, the soil is easily converted into a material having a specific volume equivalent to what could otherwise only be obtained by subjecting untreated soil to a long-term consolidation at a consolidating pressure of 1000kPa.
3) After compaction, the treated soil turns into a de-structured and overconsolidated clay soil with mechanical properties of low compressibility and high shear resistance.

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