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Hardening of soil improved by deep mixing method

Durcissement des sols améliorés par la méthode du mélange en profondeur

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SYNOPSIS The deep mixing method (DM method) for strengthening thick deposits of weak sedimentary soil by mixing, in-situ with a strengthening agent is now widely used in Japan. The authors have studied the mechanism which produces this strengthening. The result of their study indicate that adsorption and the pozzolanic reaction in the soil as well as the reaction of the strengthening agent itself, contribute greatly to the increase in strength of the various soils. This provides a uniform basis for explaining the complicated soil strengthening process and explains why the same treatment used in different soils produces a wide variation in results.

INTRODUCTION

The method of strengthening weak clay soils by mixing in situ with a dry type hardening agent was developed about 1975 simultaneously in Sweden and Japan. The hardening agent used in both cases was quicklime. Later, in Japan, ordinary Portland Cement was used as the hardening agent and it was applied as a slurry (i.e. mixed with water) rather than in dry form. This appeared to produce a more uniform mixture of the hardening agent with the in situ soft soils which increased both strength and uniformity in the improved soil. Due to its superior performance in these areas, this method was accepted and used widely throughout Japan especially in marine projects.

Various engineering properties of cohesive soil improved by mixing with a ordinary Portland Cement slurry were reported by Kawasaki et al. (1981 and 1983). However, these reports failed to explain fully why the same improvement procedure applied to different soils produced varying results. In order to determine this it is important to attempt to define the mechanism that produces the soil strengthening by studying the characteristics of the strengthened soil in relation to the in situ soil properties and the characteristics of the hardening agent. The authors consider that the improved soil consists of hardened cement particles and also soil particles hardened as a result of the pozzolanic reaction between the soil and products of the cement hardening process and intend to identify the mechanism by which this occurs.

PROPERTIES OF SOILS AND CEMENTS USED IN TESTS

Samples from 3 kinds of marine clay soils and 3 other soils having a relation to the clays in the marine soils were used in the testing. The marine clay soils samples were taken from Yokohama, Osaka and Imari. The other soils were kaolin, bentonite and a volcanic ash type clay ("Kanumatsuchi").

TABLE I

Properties of Soil Used

Properties \ Name of Sample	Marine Clay			Kanuma-tsuchi	Kaolin	Ben-tonite
	Yoko-hama	Osaka	Imari			
Specific Gravity	2.776	2.674	2.632	2.495	2.715	2.978
Water Content (%)	100	100	90	100	130	1020
Liquid Limit (%)	88.0	65.7	70.4	NP	50.8	461.4
Plastic Limit (%)	31.9	22.4	24.2	NP	31.6	25.1
Plasticity Index	56.1	43.3	46.2	–	19.2	436.3
Sand Content (%)	9.9	28.5	2.2	6.5	0	0
Silt Content (%)	44.0	26.1	44.5	51.1	35.1	31.3
Clay Content (%)	46.1	45.4	53.3	42.4	64.9	68.7
Humus Content (%)	0.6	0.3	0.5	0.1›	0.1›	0.1›

The physical and chemical characteristics of the soil samples are shown on Table I. The mineral content of the marine soils (clays) used, based on the "X-ray Powder Diffraction Method" proposed by Oinuma were reported by Kawasaki et al. (1983) and are not repeated in this paper. The content of amorphous materials in the soils was determined by the "Weight Loss at 200°C Method" proposed by Kitagawa (1977) and was 9.6, 4.1 and 4.1 percent respectively for the Yokohama, Osaka and Imari soils provided that the grain size of the samples was under 74 µm.

The hardening agent used in the tests was a mixture of ordinary Portland Cement (OPC) and blast furnace slag (slag) blended at various ratios. This mixture was selected because it is quite often used in actual construction projects in Japan. The "Blaine Fineness" of OPC and slag was 3300 and 3410 (cm^2/g) respectively.

CHEMICAL REACTION BETWEEN SOIL AND HARDENING AGENTS, AND SCHEMATIC ILLUSTRATIONS OF IMPROVED SOIL

The Chemical reactions between a cohesive soil, ordinary Portland Cement and blast-furnace slag and their reaction products, in general, are shown in Fig. 1. When OPC is used as a hardening agent, the following reactions occur: (a) hydration of OPC producing $Ca(OH)_2$ (b) adsorption of $Ca(OH)_2$ by clay (or a cation exchange reaction) until the clay is saturated with $Ca(OH)_2$ and from that point (c) the pozzolanic reaction between clay and $Ca(OH)_2$ will occur. When a mixture of slag and OPC is used as a hardening agent, slag hydration due to alkaline activation of $Ca(OH)_2$ occurs in addition to the above-mentioned reactions. In both cases, $Ca(OH)_2$ produced by hydration of OPC plays an important role in the hardening of the improved soil.

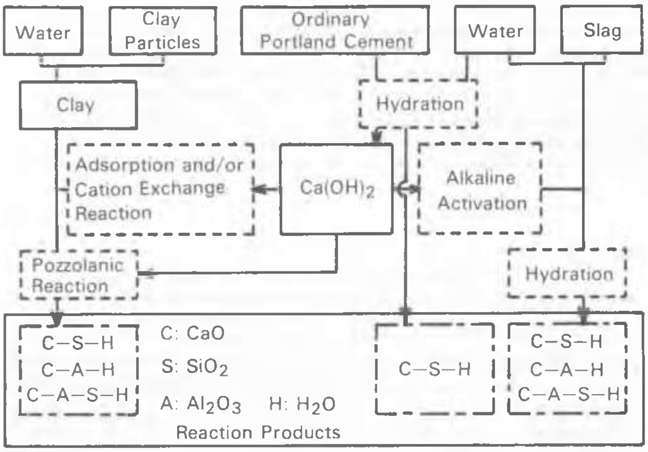

Fig. 1 Chemical Reaction between Soil and Hardening Agents

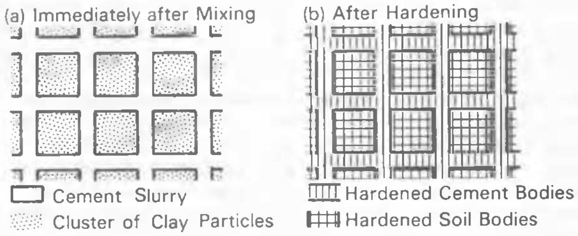

Fig. 2 Schematic Illustrations of Improved Soil

It is proposed to illustrate the conditions of hardening with the schematic diagrams shown in Fig.2 above. Fig. 2(a) shows the condition immediately after mixing a cohesive soil and a hardening agent slurry. It is considered that even if the cohesive soil and hardening agent slurry are thoroughly mixed, clay particles will form into clusters which will be surrounded by the slurry. Fig. 2(b) shows the condition after cohesive soil and hardening agent slurry have formed a hardened body. Here the hardening agent slurry shown in Fig. 2(a) produces hydrated calcium silicates, hydrated calcium aluminates, $Ca(OH)_2$, etc., and forms hardened cement bodies. The pozzolanic reaction between the clay and the $Ca(OH)_2$ produced by the cement hydration reaction produces hardened soil bodies. It is considered as shown in Fig. 2 that the strength of the improved soil will depend upon the strength characteristics of both types of hardened bodies.

STRENGTH CHARACTERISTICS OF HARDENED SOIL BODIES AND HARDENED CEMENT BODIES

Strength characteristics of the hardened soil bodies are governed by the $Ca(OH)_2$ adsorption and the pozzolanic reactivity of the soils. The hydration of OPC produces $Ca(OH)_2$ which is first adsorbed by the clay to the point of saturation. This adsorption does not produce an appreciable increase in the soil strength. If additional $Ca(OH)_2$ is available after saturation the pozzolanic reaction between the clay and this free $Ca(OH)_2$ will occur. The pozzolanic reaction will produce a dramatic increase in the strength of the soil. Thus as $Ca(OH)_2$ is added to a clay in increasing amounts, the point where a dramatic increase in soil strength occurs indicates the point where the soil is saturated by the $Ca(OH)_2$ and the pozzolanic reaction has started. The dosage at that point then will indicate the maximum amount of $Ca(OH)_2$ that can be adsorbed by the soil.

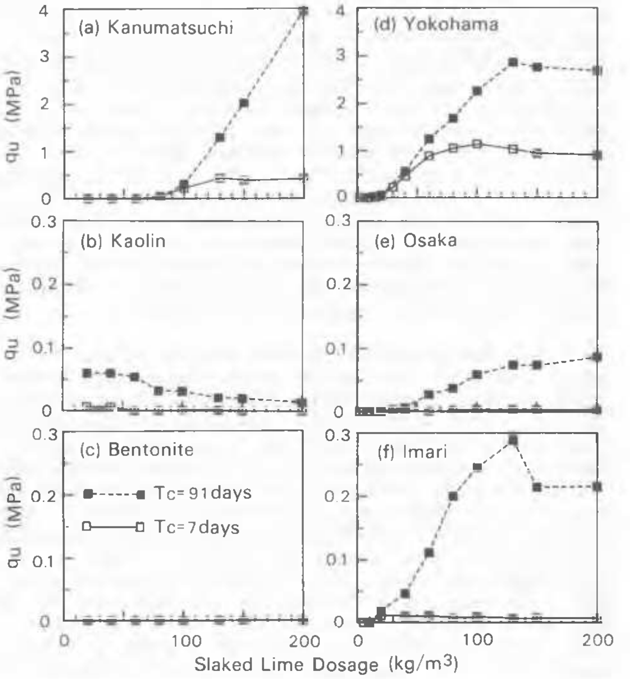

Fig. 3 Test Results of Slaked Lime Treated Soil

Fig. 3 indicates the strength/dosage relationship of the test soils which have been treated with $Ca(OH)_2$ (Slaked Lime). The dosage of slaked lime was increased from zero to 200 kg/m^3 for all six soils. As can be seen, the Kanumatsuchi soil (whose main constituent is allophane, one of the amorphous clay minerals) displays the greatest adsorption with a saturation point of between 80 and 100 kg/m^3 of $Ca(OH)_2$. This is followed by the three marine clay soils which all have lower adsorption capacities. The kaolin and bentonite indicate no capacity for $Ca(OH)_2$ adsorption.

The pozzolanic activity of the soil can be judged by the increase in strength of the soil after adsorption saturation has been reached. In this respect, the Kanumatsuchi, and Yokohama soils show a high pozzolanic reactivity while the remaining 4 soils were rather low. [Please note that the strength scales on Figs. 3(a) and 3(d) are different that those on Figs. 3(b), 3(c), 3(e), and 3(f).] These strength also appear to corresponded to the amorphous material contents of the soils.

For the strength characteristics of the hardened cement bodies in the improved soil, the test results reported by Maruyasu et al. (1970) as shown in Fig. 4 will apply. Fig. 4 indicates compressive strength of cement mortor where the hardening agent consists of various blends of OPC and slag.

The figure suggests that hydration of slag is slower than that of OPC. Also, as the quantity of slag increases, the quantity of $Ca(OH)_2$ (which is generated by the hydration of the OPC) becomes smaller which produces a finer microstructure. Strength characteristics of the hardened cement bodies in the DM improved soil are considered similar to those shown in Fig. 4.

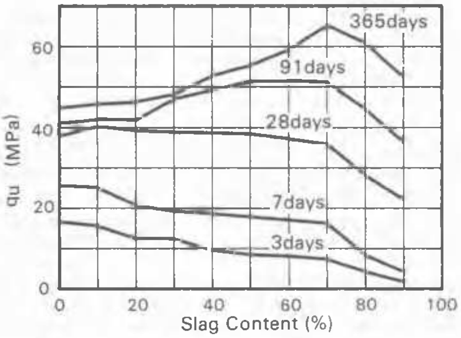

Fig. 4 Test Results of OPC-Slag Mortar (after Maruyasu et al.)

RESULTS OF UNCONFINED COMPRESSION TESTS OF VARIOUS SOILS AND THEIR DESCRIPTION

Strength tests were conducted on test specimens of soils treated with a hardener composed of a blend of OPC and slag. The hardener was applied as a slurry with three hardener dosage rates (200, 150 and 100 kg/m^3) and with a water/hardener ratio at a constant 60%. The persentages of OPC and slag composing the hardener were varied. Test results are shown in Figs. 5 and 6.
By examining Figs. 5 and 6 two main features are apparent as follows:

(i) The OPC/slag ratio which provides the maximum unconfined compressive strength in the improved soil varies according to the type of soil, dosage of hardening agent and age.
(ii) The effects of the improvement vary according to the soil type even among soils with nearly the same relative water content treated with identical dosages of hardening agent.

We shall attempt to explain the experimental results shown in Figs. 5 and 6 by means of schematic diagrams (Fig. 7), using the characteristics of hardened cement and hardened soil bodies. The assumptions used are as follows:

(i) The improved soil consists of hardened cement and hardened soil bodies.
(ii) The strength characteristics of the hardened cement bodies are in accordance with Fig. 4.
(iii) The strength characteristics of the hardened soil bodies are in accordance with Fig. 3.
(iv) Hydration of OPC generates calcium hydroxide amounting to 25% of its weight.
(v) The calcium hydroxide generated is first adsorbed by the clay then the remainder is used in pozzolanic reactions and slag hydration.

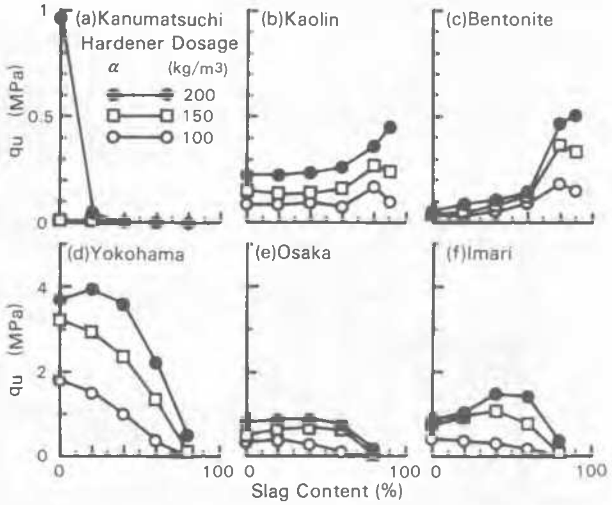

Fig. 5 Test Results of Improved Soil (Tc = 7 days)

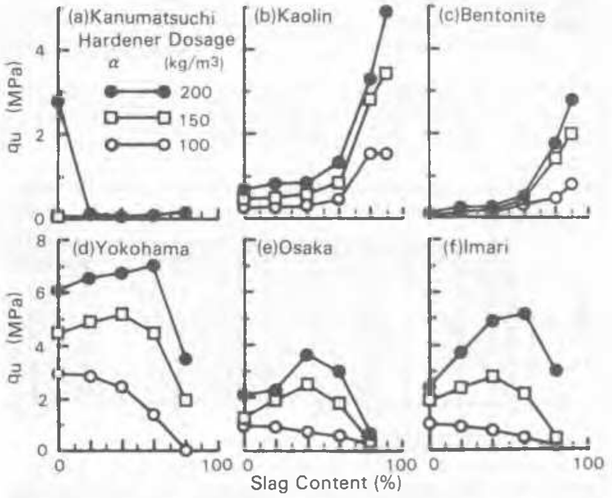

Fig. 6 Test Results of Improved Soil (Tc = 91 days)

(vi) Only a trace quantity of calcium hydroxide is required for slag hydration.

Fig. 7 (a) shows the state of hydration, after long aging, of hardening agents with various blending ratios of OPC and slag. For example, the blend corresponding to the line A-A is slag 40% and OPC 60%. At the hardening agent dosage of 200 kg/m^3 this means OPC 120 kg/m^3 and slag 80 kg/cm^3. In the OPC hydration, 30 kg/m^3 (= 120 × 0.25) of calcium hydroxide is generated, 15 kg/m^3 of which is adsorbed in the clay, and the remaining 15 kg/m^3 is used in pozzolanic reactions and slag hydration. The line B-B indicates the boundary between occurrence and non-occurrence of slag hydration. At line C-C the blend is 80% slag and 20% OPC. Since the quantity of calcium hydroxide generated is small (10 kg/m^3), it is entirely adsorbed by the clay, and all the slag remains unhydrated. On the basis of Fig. 7(a), the strength of the hardened cement bodies, hardened soil bodies and improved soil are illustrated in Fig. 7 (b), (c) and (d) respectively.

With reference to Fig. 7 (a), we can determine that the OPC/slag ratio which provides maximum unconfined compressive strength in the improved soil increases as (a) less adsorption of slaked lime in the soil occurs or (b) as larger dosages of hardening agent are applied or (c) with greater age.

Figs. 8 (a) thru (d) show the diagrams for the various soils as in Fig. 7(a). We can explain qualitatively the strength of improved soils

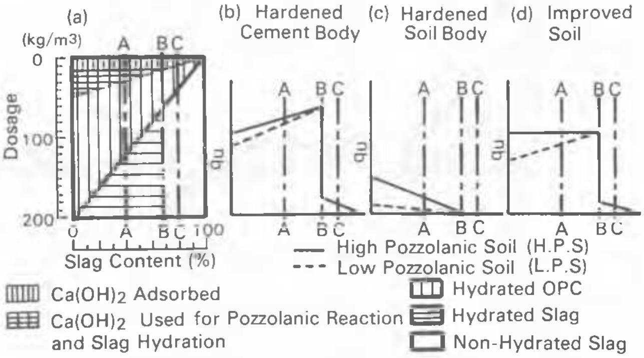

Fig. 7 Diagram for Description of Strength of Improved Soil [Dosage of Hardening Agent (α) = 200 kg/m^3]

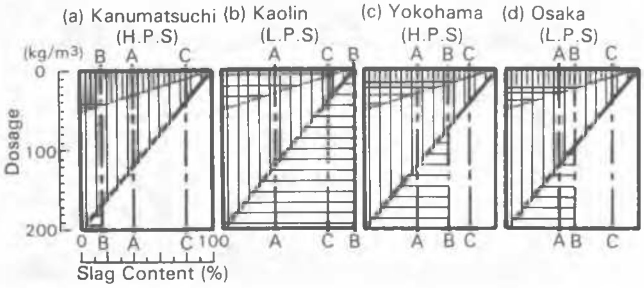

Fig. 8 Diagram of Description of the Strength of Various Improved Soils [Dosage of Hardening Agent (α) = 200 kg/m^3]

shown in Fig. 5 and Fig. 6 on the basis of Fig. 8, though the detailed explanation will be abbreviated.

CONCLUDING REMARKS

The points which have been clarified by the present research are summarized below.

i) The idea that the soil improved by the DM method consists of hardened soil bodies and hardened cement bodies, can adequately explain, in a unified manner, the strength characteristics of improved soils for various types and quantities of cement as well as various types and qualities of soil. In the future, this approach may be expected to provide a semiquantitative or quantitative method of estimating strength by considering the ratio of the contributions of the hardened soil and hardened cement bodies.

ii) In the case of soils with lower pozzolanic reactivity, the strength characteristics of the hardened cement bodies largely govern the strength characteristics of the improved soil. On the other hand, soils with higher pozzolanic reactivity produce stronger hardened soil bodies and finer hardened cement bodies by reacting with the calcium hydroxide generated by the hydration of the cement contained in the hardening agent. Therefore, all other factors being equal, greater strength is manifested in soils with high pozzolanic reactivity.

iii) The adsorption and pozzolanic reactivity of the clay constitute important factors in understanding the hardening characteristics of improved soils. Solidification tests of clay using slaked lime are effective in providing these data.

iv) As hardening agents in the deep mixing method, ordinary Portland Cement and Portland Blast-Furnace Slag Cement are more advantageous than quick lime and slaked lime from the viewpoint of wide applicability to various types of soil.

REFERENCES

Kawasaki, T., Niina, A., Saitoh, S., Suzuki, Y. and Honjyo, Y., (1981), Deep Mixing Method Using Cement Hardening Agent, Proc. 10th ICSMFE, Vol. 3, pp. 721-724, Stockholm

Kawasaki, T., Saitoh, S., Suzuki, Y. and Babasaki, R., (1983), Ground Stabilized by Deep Mixing Method, Proc. 7th ARC, SMFE, Vol. 1, pp. 249-254, Haifa.

Kitagawa, Y., (1977), Determination of Allophane and Amorphous Inorganic Matter in Soils, Bulletin of the National Institute of Agricultural Sciences (in Japanese with a summary in English), No. 29

Maruyasu, T., Kobayashi, K. and Sakamoto, Y., (1970), Studies on Portland Blast-Furnace Slag Cement Concrete, Concrete Library (in Japanese), No. 25