Soft Ground Improvement by Deep Cement-Mixing Technique in Southern Vietnam

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ABSTRACT: This paper examines the application of deep cement-mixing technique in improving engineering properties of soft grounds at nine different sites in southern Vietnam's typical soft soil deposits. The exercise consisted of running a series of laboratory tests on undisturbed soil samples and their mix designs with cement, and of field trials followed by field application of 500,000 m of the cement treated columns having 600mm diameter. The field treatment was done using Dry Jet Mixing (DJM) technique. After the field trials and applications, cores were extracted from the treated grounds to evaluate improvement in their engineering characteristics. Both the laboratory and the field results revealed a drastic enhancement in strength, stiffness, and permeability of the treated soft soils, thus establishing the deep cement-mixing technique's capability to treat southern Vietnam's soft grounds.

KEYWORDS: Deep cement-mixing technique, Dry mixing method, Soft ground, Uniaxial compressive strength, Stiffness, Permeability

1. INTRODUCTION

In southern Vietnam, pervasive soft grounds possess a major challenge in meeting the region's physical-infrastructure development needs (see for example, Cook and Tuan 2013; Hung et el, 2013). Treatment of such soft grounds by mixing the soft soil with cement has the potentiality to provide a viable option to address the issue by enhancing such engineering properties as compressive strength, stiffness, and permeability of the ground (see for example, Kitazume and Terashi, 2013; Hartlen and Wolski, 1996). This paper examines the applicability of deep cement-mixing technique in improving the engineering characteristics of southern Vietnam's soft grounds, by executing a series of laboratory and field investigations at nine distinct sites.

Deep cement-mixing technique—in which soil in-situ is mixed mechanically with cement—is gaining popularity in many countries to improve engineering characteristics of soft grounds, see for example, Kitazume and Terashi (2013), Shiwakoti and Manai (2013), Bruce *et al* (2013), Hung *et el* (2013). In many cases and circumstances, this technique bears distinct advantage over other traditional approaches such as replacing the ground, or providing piled solutions. With recent standardization of this method in Vietnam (MOC, 2006), this technique is expected to gain popularity in coming days.

A number of parameters including cement type, curing period, water-cement ratio, temperature, soil mineralogy, and activity may affect the strength and stiffness development in a treated soil (see for example, Bergado *et al*, 1996).

In field applications, deep mixing may consist of dry or wet mixing, see for example, Chida (1982). In dry mixing technique—also referred to as Dry Jet Mixing (DJM) method—dry cement is injected into deep ground using air pressure and mixed with in-situ soil. In wet mixing or slurry-jet mixing method—also referred to as Wet Jet Mixing (WJM) method—cement slurry is injected into and mixed with in situ soil.

In this study, DJM method was used for the field trials and applications.

2. INVESTIGATION PROGRAMME

The investigation was conducted at nine different sites in southern Vietnam, as a part of commercial work. The sites A to E fall on the Saigon River's west, while F to I on the east.

The investigation scheme consisted of the sites' geotechnical profiling, soil-cement mix designing at laboratory, and field trials followed by field application of about 500,000 linear metres of 600 mm-diameter-cement-mixed-columns construction using DJM method.

The geotechnical profiling exercise consisted of conducting in-situ tests including SPT tests, field van tests, and various laboratory tests on undisturbed soil samples.

Details of the laboratory-mix design, field trials, and field application works are as follows.

2.1 Laboratory Mix Design

Undisturbed soil samples were extracted at various depth intervals using thin-walled tube samplers. The tubes with samples were sealed by vinyl tape at the site before transporting to the laboratory. There the samples were pushed out from the tubes, wrapped with plastic foils, and stored in air-tight container box to avoid any moisture loss.

For the soil-cement mix design, two commercially available cements were used: Nghi Son (Portland Cement Blended 40 (PCB40)) and Holcim Ready Flow (TCVN 6260-1997, PCB40). They are designated as type A and type B, respectively. For the mix designs, cement contents varying from 100 to 250 kg/m^3 of soil were applied to achieve target design strengths. The test procedure for the mix followed JGS 0821-2000.

Using rotary mixing machine, every lot of soil samples extracted by sampling from each site was mixed for uniformity. If one sample differed distinctly from the other one, they were mixed in separate lots. Before mixing, exogenous materials such as large shells, wood chips and pebbles were removed from the soil sample, using 100mm sieve.

Cement was gradually and uniformly added in the soil sample in the mixing machine under operation (Figure 1). The mixing was done for 10 minutes, with brief interruptions in-between to mainstream the mixed soil attached to the mixing pot and the shaft.

Figure 1 Soil-cement mixing process at laboratory

The mix was then scooped into cylindrical moulds in three layers, while compacting gently and tapping the bottom part of the mould against the floor to avoid any visible cavity in the specimen. The specimen were then subjected to thermostat and humidistat box for curing at a temperature of 20±3^{o}C and a humidity of not less than 95%. At the age of 3 days, the specimen were removed from the mould, wrapped with plastic film, and subjected to further curing.

At the end of pre-determined curing age of 7 days or 28 days, unconfined compression tests on the specimen were performed following ASTM D2166.

2.2 Field Trial and Application

The mixing machine used for the field works consisted of DJM-2070 (55 kw x 2), having twin mixing shafts. Its typical site arrangement and schematic layout are shown in Figures 2 and 3, respectively.

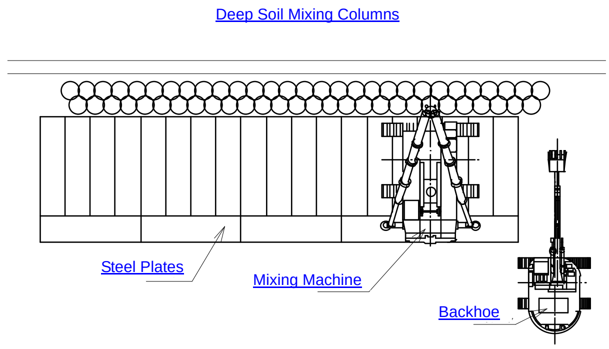

Figure 2 Site arrangement of mixing machine, backhoe and steel plates

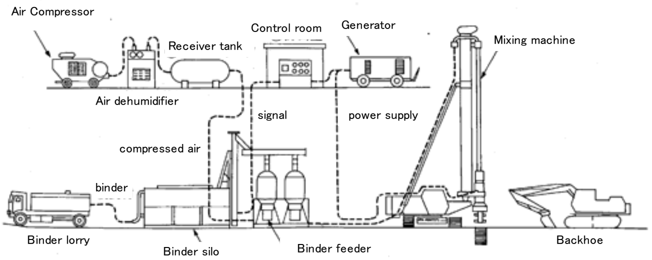

Figure 3 Layout of the cement feeding plant and other auxiliaries (DJM research group, 1984)

During the operation, twin mixing shafts are rotated down to the required depth, where the rotation is reversed and the mixing shafts slowly retrieved. Cement binder may be injected during penetration and/or retrieval process. Through the process, cement column of diameter 600 mm were created. Treated depths varied from about 10 m to 25 m, depending upon the site requirement for embankment slope stability or bearing capacity enhancement.

The following ranges of penetration speed and retrieval speed—defined as vertical movement per unit time of the mixing tool during penetration or retrieval—were used:

Penetration speed:

1.0 ~ 1.4 m/min in penetration injection system, and

1.2 ~ 1.6 m/min in retrieval injection system

Retrieval speed:

1.0~ 1.4 m/min in penetration injection system, and

0.4 ~ 0.7 m/min in retrieval injection system

During the injection, cement was supplied with compressed air through the mixing tool. Any trapped residual air-pressure was released from purpose-made empty holes in the vicinity. A few days after the executing the deep mixing at field by DJM method, cement treated columns were checked at or near the ground surface, to confirm the treated area. Figure 4 shows a typical check for the site C.

Before the field application of the cement-mixing, field trials were performed at all the six sites. Deep soil mixed columns were then constructed as a part of field application, with treatment depth varying approximately from 7m to 27m. Continuity and strength improvement of the treated grounds were examined by probing, coring, and unconfined compression tests. Besides, during the field applications, for the construction quality control, probing and coring were done on about 2% of the total installed columns.

Coring was done near the centre of treated column, by triple tube sampler of outer diameter 146mm (and inner diameter 108mm) or of outer diameter 101mm (and inner diameter 73mm).

Figure 4 Surface exposure of cement mixed column

3. TEST SITES' GEOTECHNICAL PROFILE

Figure 5 shows the soil profile of all the nine sites, whose soft layers consist of highly compressible Holocene soil deposits. The profile includes field vane strength (Su), natural water content (wn), liquid limit (LL), and plastic limit (PL) plotted against depth of existing grounds.

These soils are very soft to soft, blackish grey organic clay, organic silt, or sandy organic clay, and are classified as OH, MH or CL. Their typical water content range from 42 to 134%, with shear strength as low as 3-10 kPa. Their average clay contents is 50% and silt contents is 45%. Their organic contents vary between 2 to 16%, and pH from 6.1 to 8. Similarly, their chlorine (Cl), sulphate (SO3) and salt (NaCl) contents vary in the range of 0.14~0.59%, 0.01~0.32% & 0.28~1.2%, respectively.

4. RESULTS AND DISCUSSIONS

4.1 Influence of pH and Organic Content

Figure 6 examines the effect of pH on uniaxial-compressive strength of the cement-treated soil at sites E to I. Applied cement contents vary between 100 to 200 kg/m^3.The results are based on 28-day aged laboratory-mixed samples.

Despite academic criticism on ability of unconfined compression test to give reliable strength result of soil mixes, recent researches have established that such tests can reasonably be used in practice. Finite element studies by Namikawa, Hiyama, and Nakashima (2013) simulating the unconfined compression behaviour of cement-treated soils have shown that despite spatial variation of the compressive strength, mean strength of the parts comprising the sample remains the same.

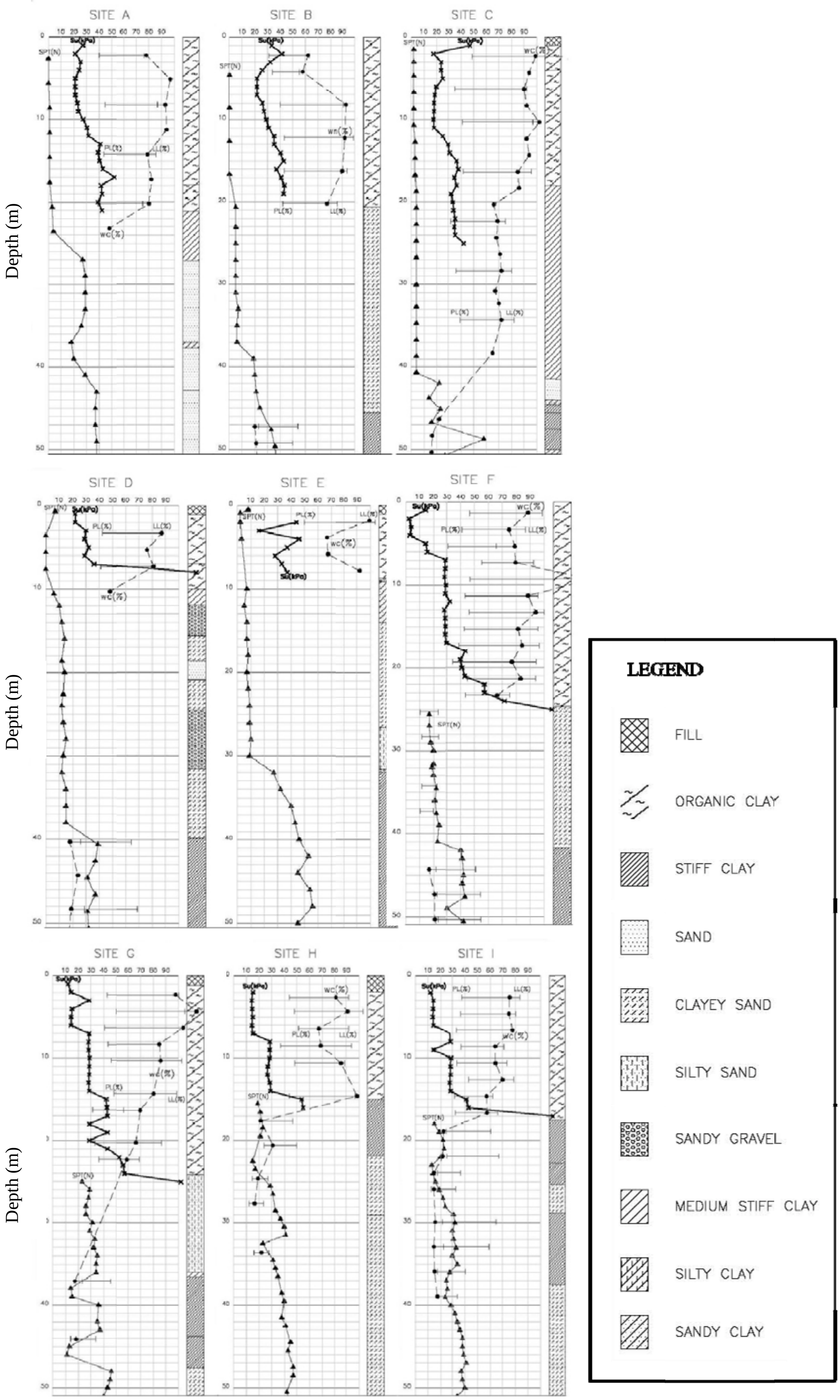

Figure 5 Soil profiles of tested sites (completed)

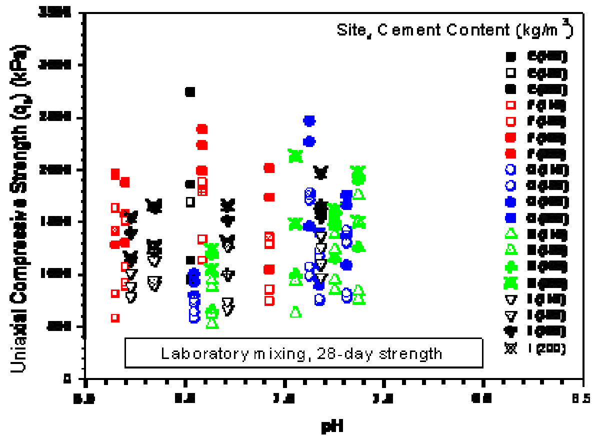

Figure 6 Effect of pH in compressive strength of cement treated soil, sites E~I

It may be noted that the investigated sites have pH values on either side of the neutral point 7.0. Change in pH value does not noticeably influence the undrained shear strength, though the cement-content's influence is obvious.

Figure 7 shows the effect of organic content on uniaxial-compressive strength for 28-day aged laboratory-mixed samples, for the sites E to I.

Organic contents of the investigated sites vary from about 2% to 16%. For the full range of organic content under investigation, the cement treatment significantly increases the uniaxial compressive strength. Though the general trend shows the strength decrease with the organic content increase, the strength variation band is predominantly governed by the applied cement content.

These results show that despite wide variation in pH and organic contents, the soils are treatable by mixing with cement.

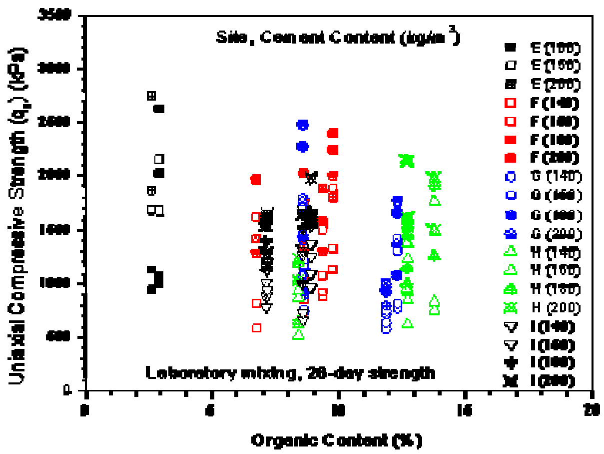

Figure 7 Effect of organic content in compressive strength of cement treated soil, sites E~I

4.2 Influence of Moisture Content and Cement Type

Figure 8 shows a typical relationship between natural water content of the soil from the site C and uniaxial compressive strength of its laboratory mix—for the cement contents of 100, 150 and 200 kg/m^3.

The results show that the cement treatment responds well to wide range of water content existing at the site. No noticeable relation exists between the soil moisture content and the cement-mix's strength attainment.

The cement treatment, however, dramatically increases the mix's uniaxial compressive strength, crossing 500 kPa mark and reaching as high as 3000 kPa. For the tested mix range, the trend of achieving higher strength with an increase in cement content is plain.

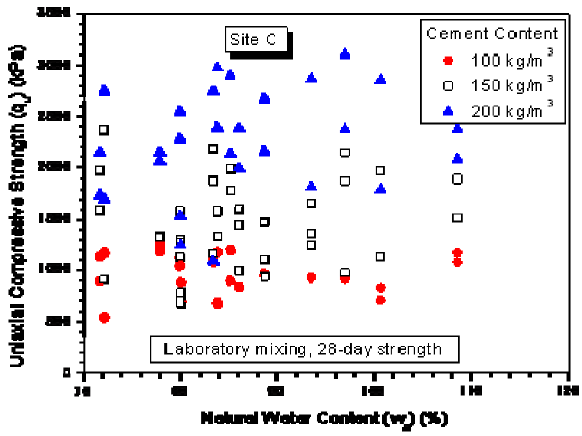

Figure 8 Effect of water content in uniaxial compressive strength of cement treated soil, site C

Figure 9 compares the uniaxial compressive strength variation with water-cement ratio for the sites E, F, G, H, I. In the laboratory mix design, two cement types were tested, type A and type B. Two observations may be made. Generally, lower the water-cement ratio, higher the compressive strength of the treated soil. This trend is consistent with the earlier observation that higher strength is achieved when the cement content is increased.

Secondly, cement type may influence site-specific strength performance, though such effect may not be critical. Here, for a given cement proportion, the type-B cement yielded higher strength at the site E, while the type-A cement did better in all the other sites.

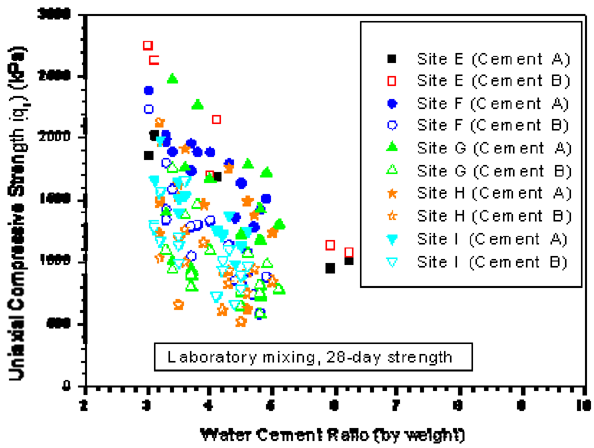

Figure 9 Effect of water cement ratio in compressive strength of cement treated soil

4.3 Influence of Curing Duration

Figure 10 compares the uniaxial compressive strength results of the 7-day and 28-day cured cement-treated soil samples taken from the site E. For the investigated cement-content range, 28-day strength is linearly related to 7-day strength.

Figure 11 plots the 7-day vs. 28-day strengths of laboratory mixed soils from the sites E to I, for a total of 384 test results. It may be noted that—despite a significant data scatter— by curing from 7-day to 28-day, in average, the strength gained is 1.56 times.

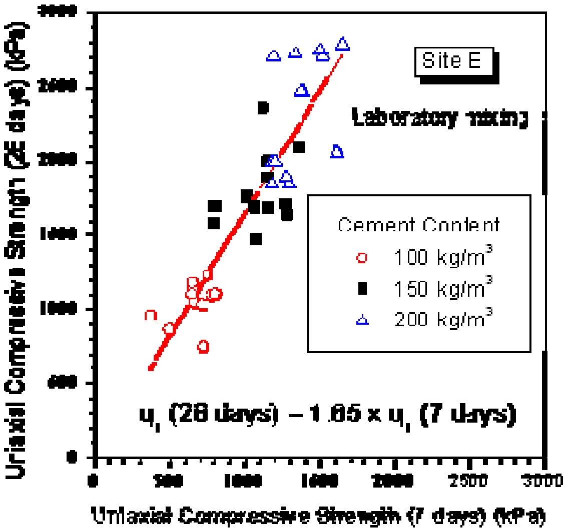

Figure 10 Strength variation with curing duration

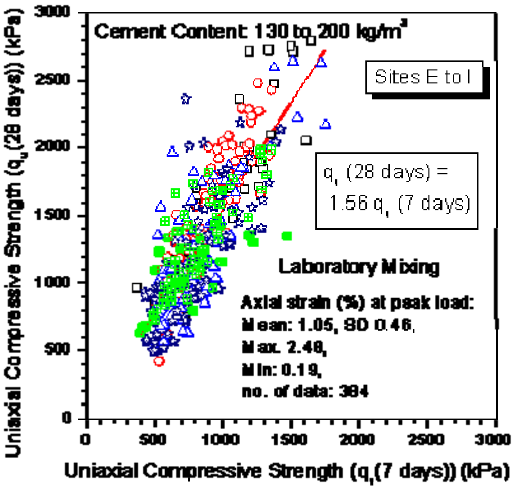

Figure 11 Variation of strength with curing duration

4.4 Influence of Specimen Diameter and Location

Figure 12 examines the influence of specimen diameter on the strength. Though strength variation with the cement content change is obvious, the variation with specimen diameter is not clear. Also, although the test results are not presented here, field treated soils extracted by two different sample sizes did not show any noticeable influence of the sampler size on the compression strength of the tested samples.

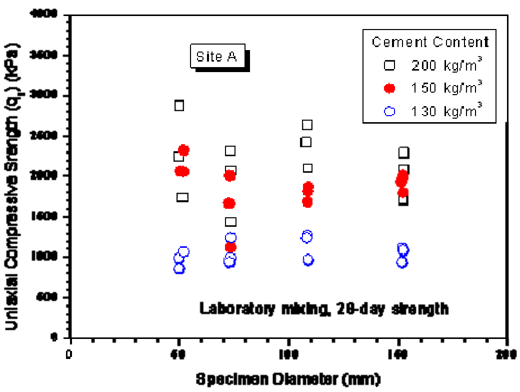

Figure 12 Effect of specimen diameter in compressive strength of cement treated soil

Figure 13 compares strength variation along the sampling-tube length of cored sample from the cement-treated column at the site E. It may be noted that, within the investigated cement-content range, the compressive strength increases almost linearly with the increase in cement content. But for a given cement content, hardly any change in the strength pattern can be seen for the specimen extracted from top, middle or bottom part of the sampling tube.

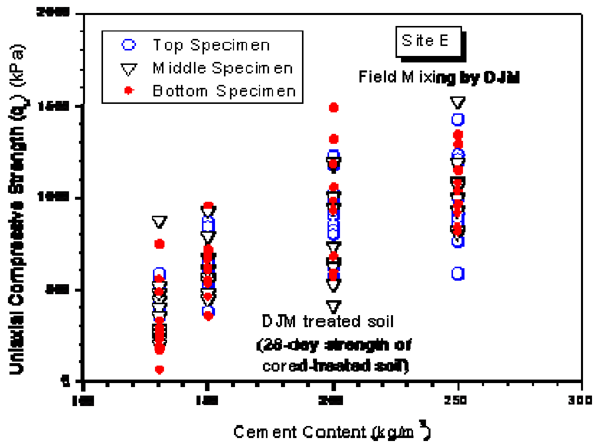

Figure 13 Effect of specimen location in compressive strength of cement treated soil

4.5 Strength Increase at Laboratory versus Field

Figure 14 compares the uniaxial compressive strength of laboratory mix and field mix at the site E. The cement-treated soil samples were tested at 28-day age.

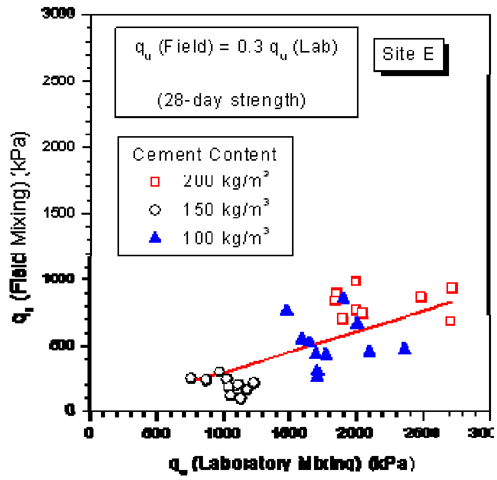

Figure 14 Field strength versus laboratory strength

In average, the field-treated soil strength is about 30% of the laboratory mixed soil. Considering that laboratory mixing process is closely controlled, cement and soil gets mixed up very well, so the laboratory test results yield better strength compared to the field mixes. The importance of attaining uniform mixing was also highlighted by Hung *et al* (2013), who reported lower strength for higher cement-mix proportion, due to non-uniform mix.

It is thus important to have field trials before going for full scale application of deep mixing method. Results from laboratory trials should be taken only as indicative of direction, while field trials are essential to establish suitability of particular method, equipment, and procedure, and to confirm appropriate type and quantity of cement.

Based on our experience on these sites, depending upon circumstances, more than one round of field trials might be necessary before applicability of a particular method, procedure, or cement content could be confirmed.

4.6 Stiffness Increase

In case of laboratory mixes for the sites E to I, for the cement contents varying from 130 to 200 kg/m^3 (for the data in Figure 11), the mean axial strain at peak load for 384 number of test data was 1.05%.

Figure 15 shows stress-strain behaviour of 100-200 kg/m^3 cement-treated ground, at the site E. Generally, the axial strain at peak load reduces with an increase in cement content—with the strain reducing almost three times (1.54% to 0.53%) when the cement content is doubled from 100 kg/m^3 to 200 kg/m^3.

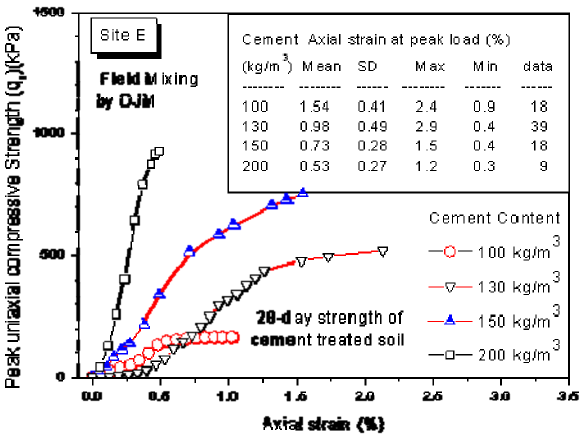

Figure 15 Stress-strain behaviour of treated soil, site E

It may be noted that Hung *et el* (2013) reported average secant modulus of elasticity of 100 MPa for cement contents varying from 11.6% to 20.5% on Mekong delta's find sand.

Thus, the cement treatment significantly increases the treated soil's compression modulus and hence reduces its compressibility. In other words, consolidation settlement beneath a loaded surface of treated ground will be reduced.

4.7 Permeability Enhancement of Treated Soil

Figure 16 compares falling-head-test based permeability of cement-treated soil with that of untreated soil, for the site C. For the treated soil, the results are based the samples extracted from field trial works. For comparison, permeability of south Vietnam's typical black sand and of typical coarse sand are also shown.

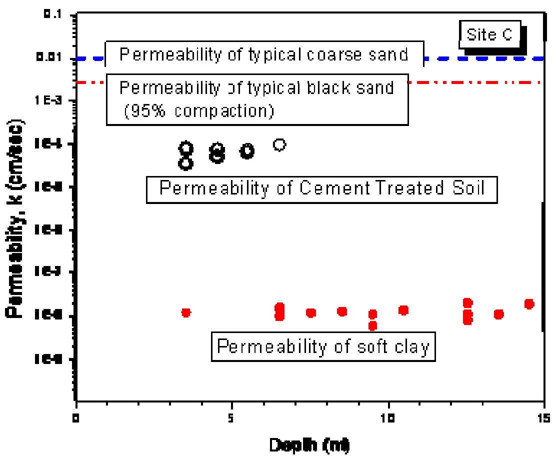

Figure 16 Permeability of DJM treated soil, site C

It may be noted that the cement treatment dramatically enhanced the treated soil's permeability. Before the treatment, permeability of the soft soil at this site was in the order of 1x10^{-8} cm/sec. After the treatment, based on the average of 25 tests, its permeability increased to 5.73x10^{-5} cm/sec, with the range varying from 3.5 x10^{-5} cm/sec to 9.6 x10^{-5} cm/sec.

Such drastic increases in permeability of cement-treated soils have also been observed in other soft soils. In soft Bangkok clay, for example, 10 to 40 times increase in coefficient of consolidation was reported by mixing 10% cement with the clay (Law, 1989).

This increase in permeability is attributed to a series of reactions that take place between the soil, water, and cement, including ion exchange, flocculation, and pozzolanic reaction (see for example, Hartlen and Wolski, 1996, Bergado *et al.*, 1996). This results in lumps of stabilized soils with weaker joints in-between and formation of layers in the columns approximately at right angle to their longitudinal axis. So, the columns act as vertical drain. This drainage function may be considered while designing cement-treated foundations (Hartlen and Wolski, 1996).

With the increase in cement content, however, after its content reaches certain limit, permeability of the treated ground is expected to decrease.

4.8 Field Strength Increase and Variation

Figure 17 compares the uniaxial compressive strength versus treatment depth, for the sites A, C and E, for the cement content of 130 kg/m^3. At each site, the strength does not follow any specific pattern with depth.

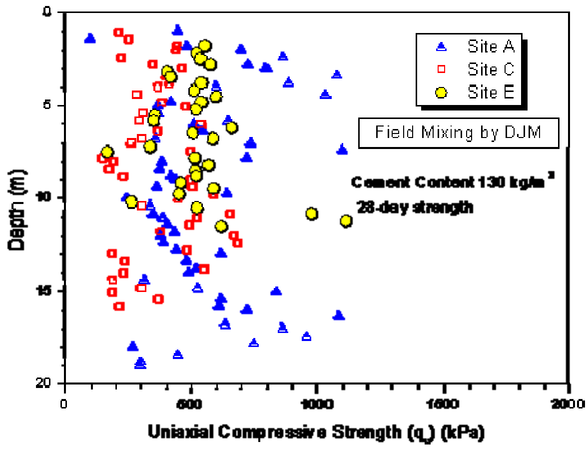

Figure 17 Strength variation with depth of DJM treated soils, sites A, C & E

Figures 18-20 depict the uniaxial compressive strength results for a large numbers of DJM treated soils from the sites A, B and C, for the cement content of 150 kg/m^3. For all the sites, compared to the in-situ strength of the ground (see Figure 5), strength enhancement after the DJM treatment is enormous. This increase in shear strength and the stiffness helps improve the bearing capacity of the treated ground.

Hung *et el* (2013) reported average unconfined strength of 1 MPa for cement contents varying from 11.6% to 20.5% on Mekong delta's find sand. Law (1989) reported up to 10 times increase in compressive strength for the Bangkok clay by mixing 10% cement with it.

The strength scatters within and across the sites are remarkable, signifying the issue raised by the strength inhomogeneity at the field. This inhomogeneity—which mainly is the function of the operation of machine and cement-treated area overlap arrangement—needs to be considered by applying suitable correction factor if a design is to base on the strength homogeneity assumption, see for example, OCDI (2002). Selection of appropriate design strength should be considered carefully considering the nature and requirement of the intended design solution.

Besides, further research may be necessary in improving the deep cement-mixing technique itself, so as to narrow the strength inhomogeneity margin.

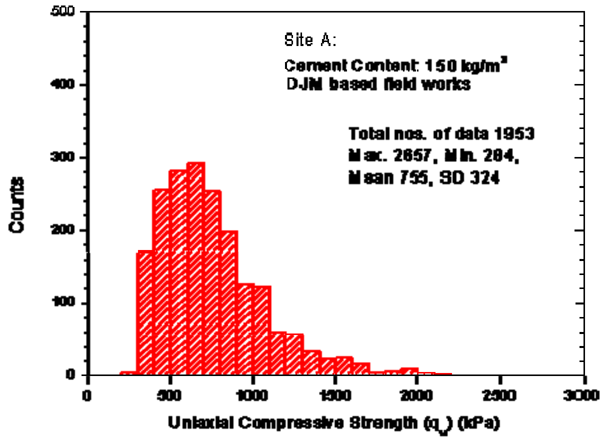

Figure 18 Strength variation, site A

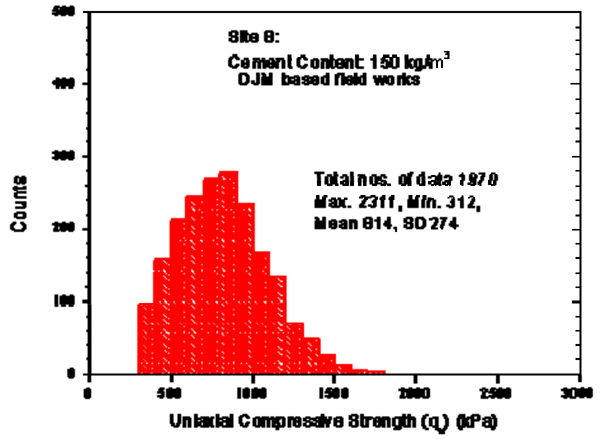

Figure 19 Strength variation, site B

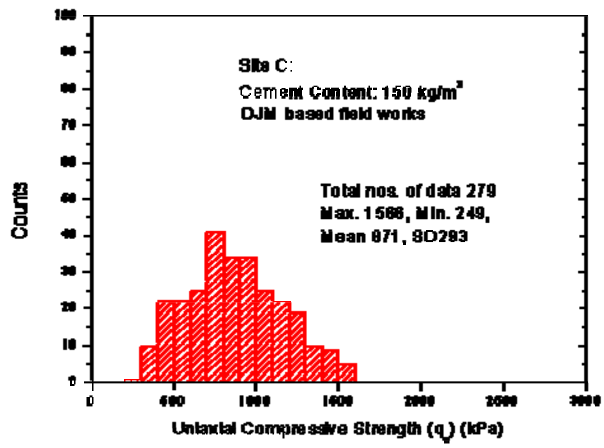

Figure 20 Strength variation, site C

5. CONCLUSION

Deep cement-mixing technique was applied in improving the engineering characteristics of southern Vietnam's soft soils, as a part of commercial work. The work included laboratory tests and full scale field trials followed by construction of 500,000 linear metres cement-mixed columns at nine different sites having diameter of 600mm, using DJM technique.

Results from the laboratory mixes as well as field trials and field applications revealed a drastic enhancement in uniaxial compressive strength, stiffness and permeability of the treated soft soils. Thus the deep cement-mixing technique has high potentiality to apply to enhance the properties of soft grounds in southern Vietnam.

Besides, further research works may be necessary on performance enhancement of deep mixing technique itself to narrow the strength inhomogeneity margin of the treated soils.

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