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UNDERSTANDING THE PERFORMANCE OF DEEP MIXED COLUMN IMPROVED SOILS - A REVIEW

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ABSTRACT

The essence of ground improvement is to enhance the engineering properties of weak soils to provide stability and sufficient bearing capacity for construction and other engineering purposes. Deep soil mixing is one method that has been widely employed for this purpose due to the environmental nature and efficiency of this method. In deep soil mixing, the amount of binder to be mixed with the weak soil depends on the initial moisture content of the surrounding soil. Several researchers have reported on this method of soil improvement through laboratory experiments, in situ testing and numerical modelling. Most literatures reviewed in this study have shown that previous studies by different researchers on weak soil improvement using deep mixing techniques have focused on the mechanical properties such as compressive strength, stiffness, modulus of elasticity and consolidation behaviour of the improved ground. For example, Ali et al., (2012), Lin and Wong, 1999, Fang et al., (2001), Porbaha et al., (2001), Yin, (2001), Porbaha, (2002), Farouk and Shahien (2013), Tao, Jim and Jing, 2014) etc. Others focused on the effect of soil type, binder type, binder content, water-cement ratio and area replacement ratio on the mechanical properties of the improved ground, for example; Nur et al. (2013), Terashi et al., (1977), Kitazume and Terashi, (2012), Farouk and Shahien, (2013) etc. This paper therefore serves as a quick guide on understanding the performance of DMC improved ground based on what has been reported in literatures.

1.0 INTRODUCTION

Location of new infrastructures on stable ground is becoming more difficult worldwide due to over population in urban areas. Most areas have been built up and countries all over the world are now being faced with the problem of non-availability of stable ground for construction purposes and other engineering activities. As a result, most construction and building projects are being channelled towards areas considered to be problematic due to the extent of underlying deposits of low strength. Due to this reason, ground improvement has become imperative for infrastructure development projects in the developed and developing countries.

For example in Japan, most constructions and building projects are located on soft alluvial clay soils, artificially reclaimed lands consisting of dredged soft clay and highly organic soils, (Kitazume and Terashi 2009). Ground conditions of this nature may pose serious problems of excessive ground settlement due to low shear strength and high compressibility and this may impair the performance and functions of the supported structure.

Figure 1.0: Installation process of a deep mixed soil column, (Massarsch and Topolnicki, 2005)

In DSM, the unstable soil is blended with cementitious and other additives to form a soil-binder column to improve strength and reduce the compressibility of the weak soil. This method mainly depends on increasing the stiffness of the native soil by adding a strengthening admixture material such as cement, lime, gypsum and fly ash. Foundations constructed using DSM techniques have been applied to support structures, embankments and excavations in countries like Japan, Scandinavia and the United States, (Kitazume and Terashi 2013).The properties of the improved soil column may reflect the characteristics of the native soil, mixing method, and the binder characteristics (Bruce, 2001).

Deep soil mixing methods are categorized into "wet" deep mixing method (WDMM) and "dry" deep mixing method (DDMM) depending on the moisture content of the native soil. In WDMM, cementitious slurry is injected through large diameter to a specified improvement depth to produce a soil-binder column. While in the DDMM, the common method is to rotate a mixing tool into the native soil to break up the soil on the down stroke, and dry reagent such as cement or quick lime or a combination of both, is pneumatically injected and blended with the soil by means of the mixing tool on the up stroke to produce a soil-binder column.

The dry DMM is generally considered less expensive than the wet DMM and also, the strength of the soil-binder column produced using dry DMM is considered to be less than the strength achieved for the same soil type using wet DMM. Some typical applications of the DSM includes; construction of embankment on soft soils, support of strip/pad and slab foundations, excavation protection walls, slope stabilization, mitigation of liquefaction potential, cut-off walls and barriers. Deep soil mixing method has also been employed in remediation of contaminated soils.

Figure 2.0: Single and extruded overlapping deep mixed soil column (Massarsch and Topolnicki, 2005).

1.1 Application of Deep Soil Mixing Method

From literature, it can be said that deep soil mixing method of ground improvement is environmentally friendly and its application in sealing and strengthening weak soils is growing across the world. Significant improvement in the physical and mechanical properties of soft soils has been achieved through the mixing of these soils with cement, lime, fly ash and other hydraulic binders to produce a soil-binder column. The resulting soil material possesses higher strength, lower compressibility and lower hydraulic conductivity, (Terashi, 2009). Typical applications of the deep mixing method in soil improvement include the following;

- Embankment stability
- Embankment settlement reduction
- Foundations of structures
- Braced excavation
- Bridge abutment
- Mitigation of liquefaction potential
- Cut slope stability
- Impact to nearby structures

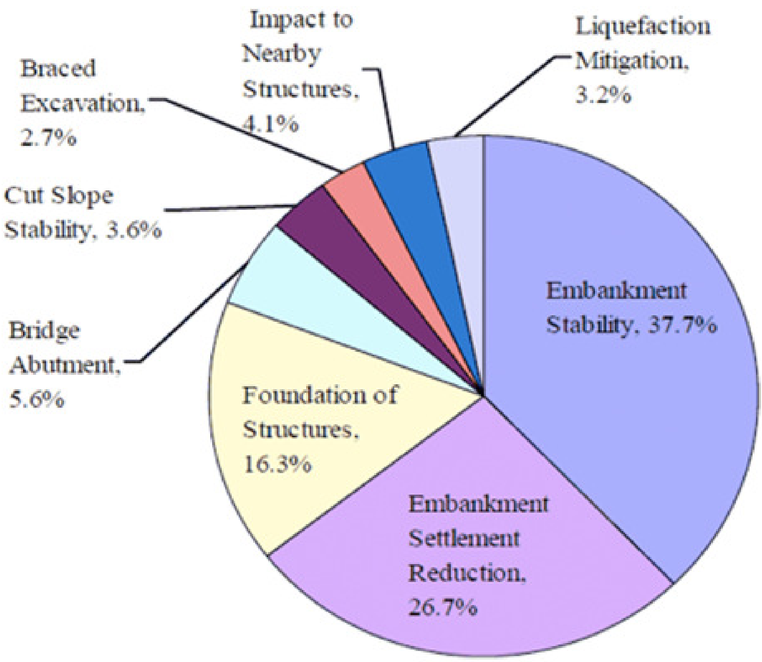

Figure 3.0: Typical areas of application for deep mixing method (Terashi, 2009)

2.0 DEEP SOIL MIXING COLUMN IMPROVED GROUND

In the application of deep soil mixing method of improvement of problematic soils, the soil columns could be installed in blocks, single columns, panels or stabilised grids depending on the purpose of improvement as shown in Figure 4.0, (Kitazume and Terashi, 2012). The installation pattern may differ from one project to the other. The diameter of these columns ranges from 0.5m to 0.75m at spacing of about 1m to 1.5m centre to centre. A 1.0m diameter column having cement content of 200 to 300 kg/m^3 and unconfined compressive strength of about 2 to 4MPa has been used to support a five storey building in Japan, (Ali, Kamarudin and Nazri, 2012). The bearing capacity and other improved parameters of the soil column may be affected by changes in diameter of the column, cement content, replacement ratio or the testing methods.

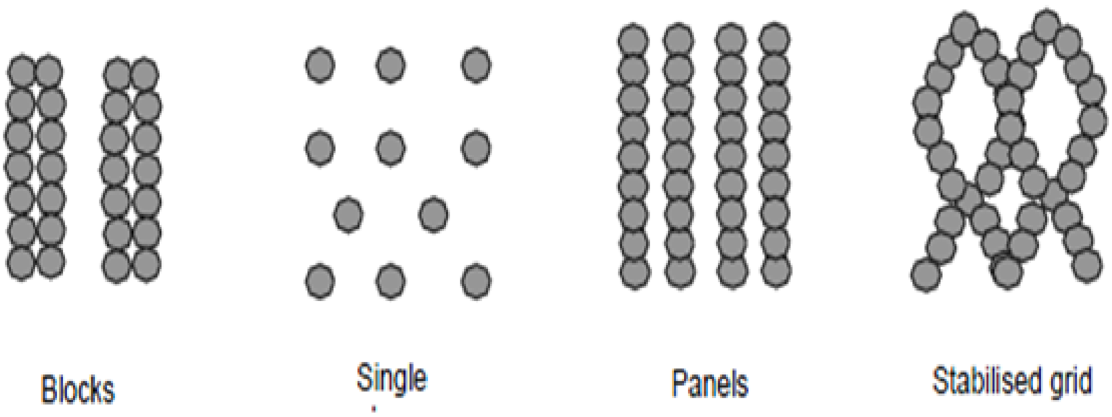

Figure 4.0: Different types of DMC installation pattern, (Kitazume and Terashi, 2012).

2.1 Strength of DMC Improved Ground

The unconfined compressive strength of deep mixed column improved ground may depend on various factors such as the type of soil, binder content, curing method, mixing time and other factors. Figure 5.0, (Kitazume and Terashi, 2012) shows the range of binder dosage and the corresponding compressive strengths for different soil types.

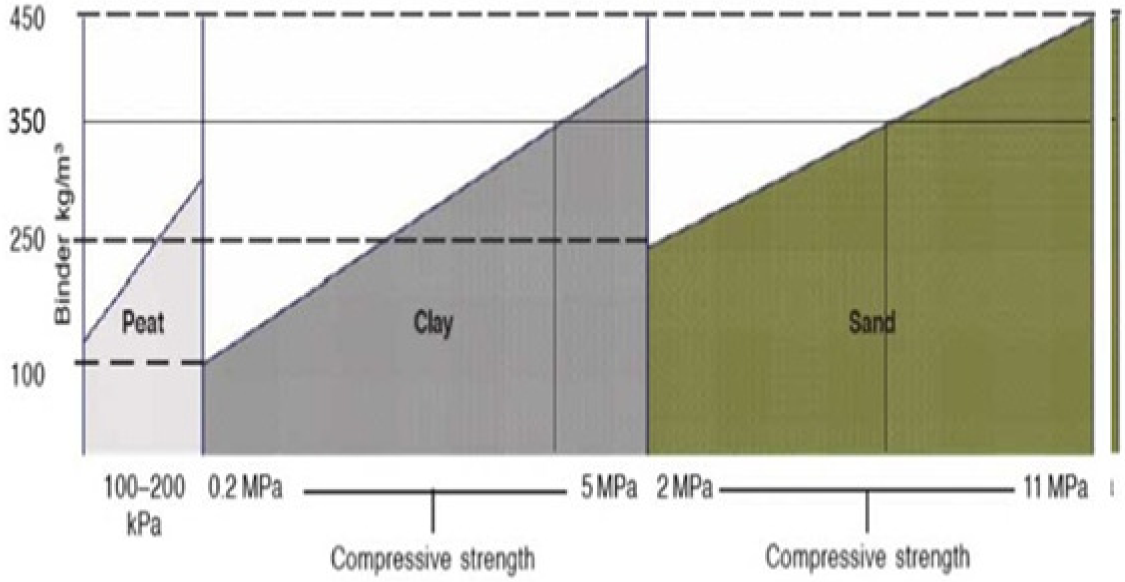

Figure 5.0 Compressive strengths of improved soils for different range of binder dosage, (Kitazume and Terashi, 2012).

The compressive strength of the treated soil may also be influenced by temperature and other environmental changes. Temperature may influence the chemical reaction between the soil and the binder. During soil binder reaction, the heat evolution of different binders may vary. In cement and lime improvement methods, the required reaction temperature comes from these binders and does not fully depend on the soft soil temperature. For curing period, EuroSoilStab, (2002) stated that the strength development in cement improved soil is during the first month and for lime improved soils; the strength development goes on for several months depending on the rate of pozzolanic reactions between the weak soil and lime.

3.0 FACTORS INFLUENCING STRENGTH OF DMC IMPROVED GROUND

3.1 Effect of soil type

Soil type influences the unconfined compressive strength of a lime improved soil as shown in Figure 6.0. The Figure shows the influence of soil type on the unconfined compressive strength of a hydrated lime improved soils collected from different locations. The improved soils were mixed at different moisture content and cured for a period of 91 days curing (Kitazume and Terashi, 2012). Figure 6.0, (Kitazume and Terashi, 2012) show that the type of soil clearly influences the unconfined compressive strength increase, irrespective of nature of the soil (marine or on-land soils). Terashi et al., (1977) reported that the grain size distribution of soil also influences the unconfined compressive strength of quicklime improved soil.

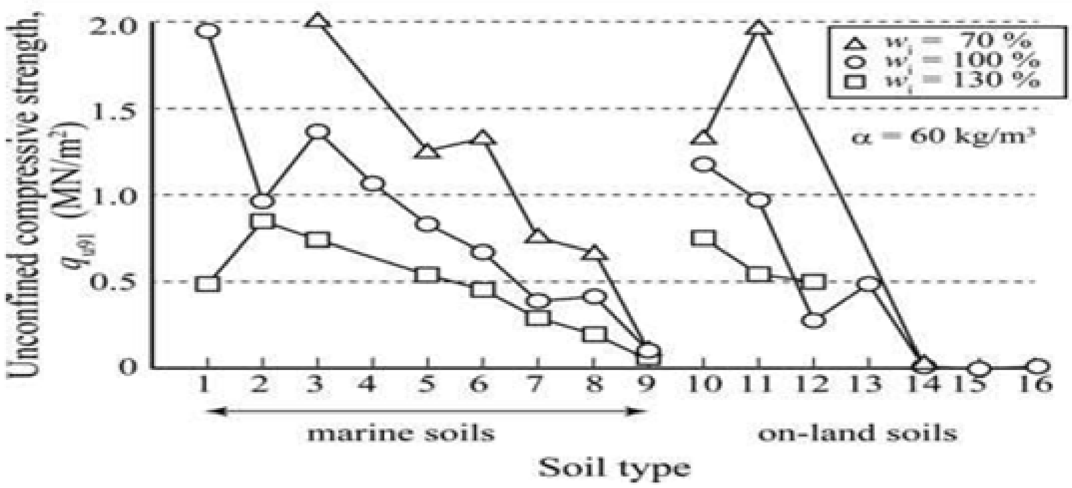

Figure 6.0 Influence of soil type on strength at 91 days curing period, (Kitazume and Terashi, 2012).

Farouk and Shahien (2013) carried out an experimental investigation on ground improvement using soil-cement columns. The first part of their study, considered two different natural silty soils extracted from the Delta of the River Nile. They investigated the effect of soil type, cement dosage and water-cement ratio on the strength of the cemented Nile delta soil. To investigate the effect of soil type, two soil types "Shobra-alnamla" (Sh soil) and "Talbantqaisar" (Tal soil) were used. These samples were mixed with the same cement dosage rate of 240kg/m^3 at different w-c ratios. They stated that cement dosage rate within the range of 120-240kg/m^3 could be used effectively in stabilizing silty soils. Winterkorn and Fang (1975) reported that cement dosage rate should range between 5% - 16% of the weight of the untreated soil but, Farouk and Shahien (2013) adopted cement dosage rate of 16.8% of the weight of the untreated soil. The second part of their study was modelling of the soil-cement column system, where the untreated soil was modelled in a rigid box made of steel and a steel loading frame with load gauges attached as shown in Figure 7.0, (Farouk and Shahien 2013).

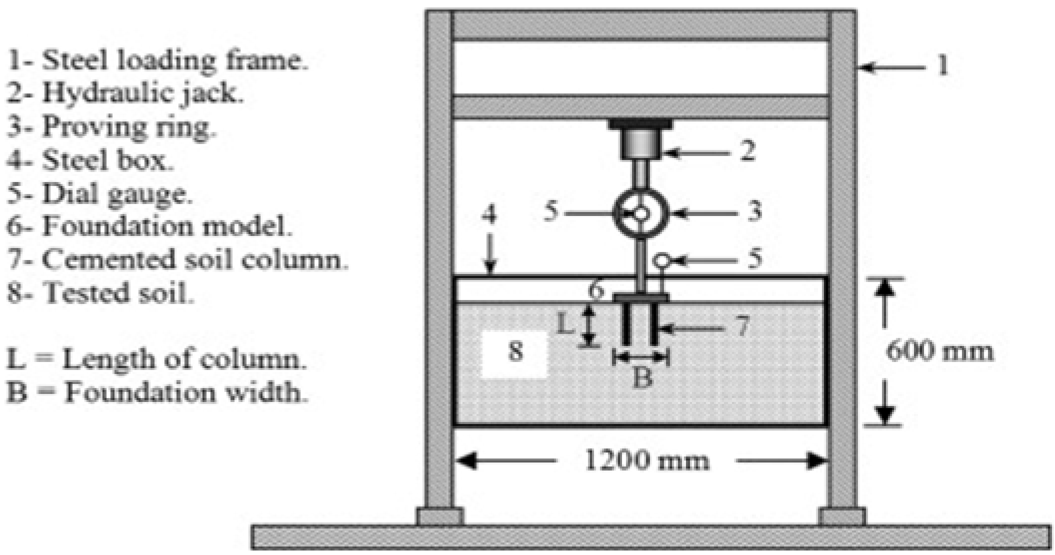

Figure 7.0: The Schematic Diagram of the Loading System (Farouk and Shahien 2013).

The soil columns were installed and aligned vertically in positions by means of wooden forms. A mattress of 10mm of the untreated soil was built at the top of the soil column (improved ground) and overlaid a $480mm \times 100mm \times 20mm$ rigid steel plate to simulate the behaviour of a strip footing on the improved soil. The steel plate was loaded by means of a hydraulic jack until reaching soil column failure.

The result of their analysis revealed that as the water-cement ratio increases, the compressive strength of the soil column decreases for both soils. Figure 8.0: shows the variation of compressive strength with water-cement ratio.

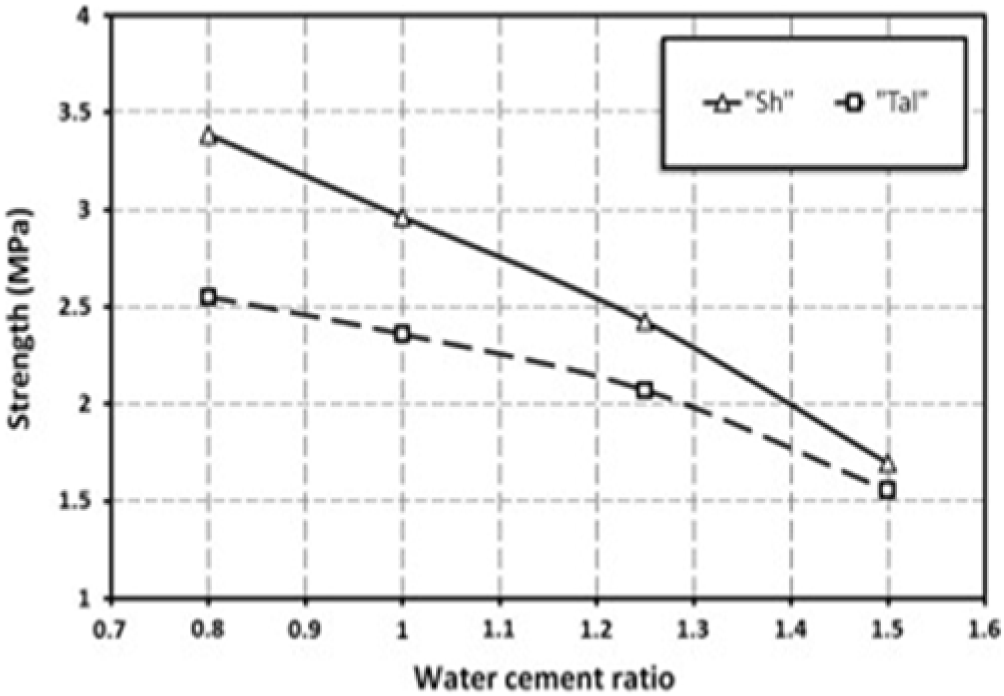

Figure 8.0: Variation of compressive strength of stabilized soil with water cement ratio (Farouk and Shahien 2013).

They claimed that, for both soil types, the effect of w-c ratio on the modulus of elasticity of the soil column is negligible within the range of w-c ratio investigated.

Their analysis on the effect of soil type on compressive strength shows that at equal w-c ratio, “Sh” soil exhibited a higher compressive strength compared to “Tal” soil. Their study also revealed that at higher w-c ratio, “Sh” soil behaves like a ductile material and a brittle material at lower w-c ratio. Figure 8.0, shows that the “Tal” soil exhibits almost ductile behaviour at all used values of w-c ratio, which they attributed to the higher fines content present in the “Tal” soil.

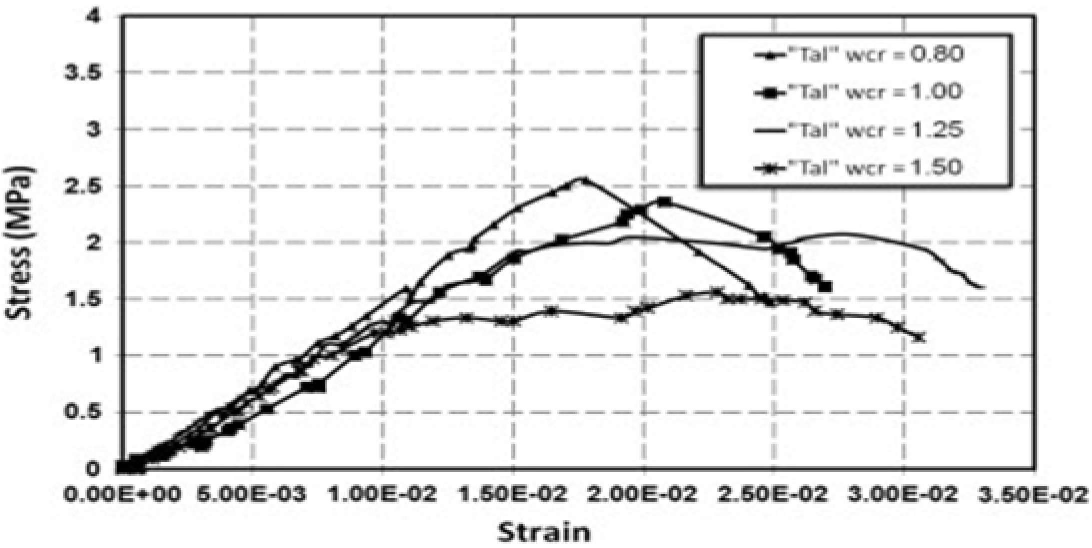

Figure 9.0: Stress strain relationship of cemented “Tal” soil at different water cement ratios (Farouk and Shahien 2013).

Farouk and Shahien (2013) concluded that compressive strength and stiffness of the improved soil decreases with an increase in fine content of the unimproved soil. The clay content of “Sh” soil was found to be greater than that of “Tal” soil by 5%, which implies that fines content has more effect on the elastic behaviour of the improved soils than the clay content.

The humic acid of the unimproved soil can affect the unconfined compressive strength and this has been investigated by Okada et al., (1983). An artificial soil was prepared by mixing varying amounts of humic acid to Kaolin clay of liquid limit and initial water content of 50.6 % and 60.6% respectively, and improved with 5% hydrated lime. It was observed that an increase in quantity of humic acid resulted to a decreases in strength, irrespective of the type of humic acid. The amount of humic acid appears to have critical influence on the strength of hydrated lime stabilized soil; this might be due to the presence of humic acid in some clay and sludge at marine and on-land areas. The unconfined compressive strength of cement improved soil depends highly on the type of cement, but decreases considerably with increasing humic acid content irrespective of the binder type. The strength reduces to about 1/3 when the content humic acid gets to about 5%. Potential hydrogen (pH) of the original soil also influences the unconfined compressive strength of a lime improved soil, such that a decrease in pH results to a corresponding decrease in strength.

3.2 INFLUENCE OF WATER CONTENT

According to Terashi et al., (1977), the water content of the surrounding soil affects the unconfined compressive strength of improved soil. When curing period is increased, the water content in the original soils provides maximum strength shifts toward the dry side but, the strength of the improved soil decreases considerably at increasing initial water content greater than the liquid limit. (Kitazume and Terashi, 2012) stated that in marine construction in Japan, this might not cause serious problem because in most cases, the natural water content of normally consolidated Japanese marine clay almost equals its liquid limit but however, care should be taken on clay soils with water content higher than its liquid limit such as on-land reclamation areas with pump dredged clay. In deep mixing method, the amount of binder is a percentage of the mass of dry soil in a given mass of the weak soil depending on the adopted mix ratio. This mass of dry soil is directly proportional to the mass of weak soil and inversely proportional to the initial moisture content. After installation of these columns, any changes in the physical properties of the surrounding soil such as change in degree of saturation, due to seasonal fluctuation of soil moisture, may affect the performance of the deep mixed column. This issue is what this research tends to also investigate.

3.3 Influence of amount of binder

The unconfined compressive strength of a weak soil increases with an increase in cement content, Nur et al. (2013). Terashi et al., (1977) studied the influence of amount of binder on the unconfined compressive strength of lime improved soil as shown in Figure 10.0, Terashi et al., (1977). Two types of marine soils (reclaimed soil and marine clay) with moisture contents 102.5% and 120% and liquid and plastic limits of 92.4% and 46.9%, and 78.8% and of 49.1%) respectively, were improved and cured for several days. For the reclaimed soil, the unconfined compressive strength increases almost linearly with amount of quicklime, irrespective of the duration of curing. While, for the marine clay, clear peak strength was reached and the amount of binder at this strength becomes even larger with longer curing time as shown in Figure 10.0, Terashi et al., (1977).

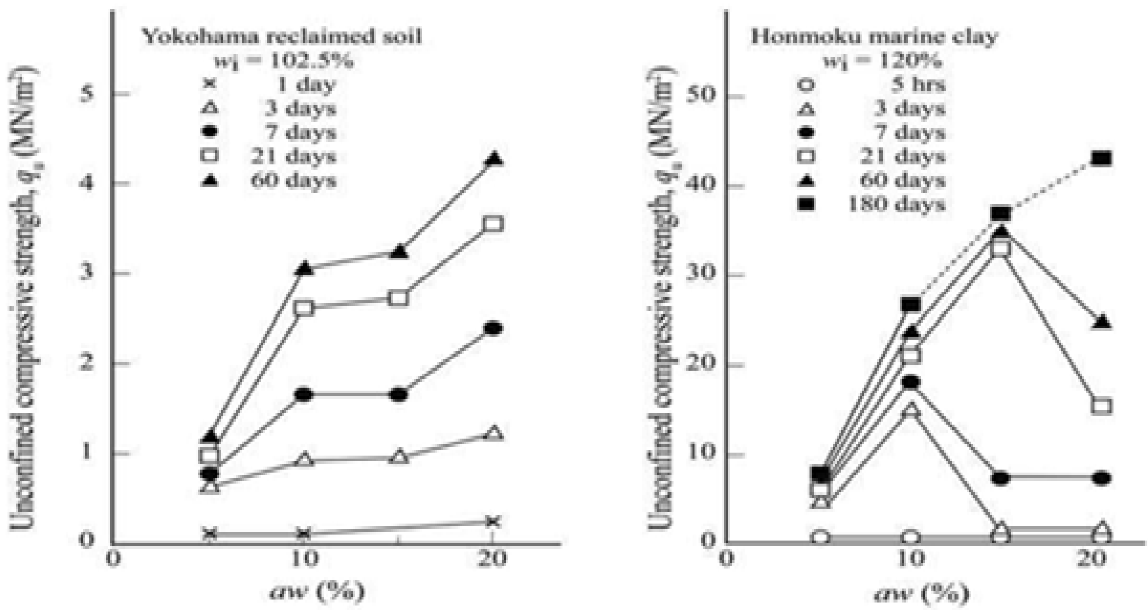

Figure 10.0: Influence of amount of binder on strength in quicklime soil improvement, (Terashi et al., 1997).

To investigate the effect of cement dose on the compressive strength of DMS column, (Farouk and Shahien, 2013) conducted a test on 'Sh' soil mixed with different cement dosage rate of 160, 200, 240, 340 and 440Kg/m^3 at a constant w-c ratio of 1.25. The effect of w-c ratio was investigated by preparing different samples of the 'Sh' soil at different w-c ratios of 0.80, 1.00, 1.25 and 1.5 at a constant cement dosage rate of 240kg/m^3. Their result on the effect of cement dosage rate on compressive strength of the soil column revealed that, at higher cement dosage rate, the improved soil exhibits a brittle behaviour. While at lower dosage rate, the behaviour tends to be ductile. They also revealed that the compressive strength and cement dosage of the improved soil are exponentially correlated.

3.4 Influence of Mixing Time

During mixing, it is expected that the mixing time should be an index, describing how the soil and binder have been sufficiently mixed. Though, other factors such as type of mixer and characteristics of the original soil to be improved in the laboratory may also influence the degree of mixing. The unconfined compressive strength of both cement and lime-cement improved soil may be influenced by this index. In a quicklime stabilization test conducted on clay with varying initial water contents and liquid and plastic limits of 87.8% and of 49.7% respectively, mixing was done at arbitrary mixing time and at 10 minutes mixing time, (Terashi et al., 1977).

The ratio of strength of stabilized soil prepared at arbitrary mixing period to those prepared at 10 minutes mixing time was recorded as the strength ratio. They observed that the strength ratio decreases considerably when the mixing period is less than 10 minutes at lower binder factor, and increases at mixing time greater than 10 minutes as shown in Figure 11.0, Terashi et al. (1977) . It was proposed that a laboratory mixing time of about 10 minutes and the use of appropriate soil mixer should be adopted.

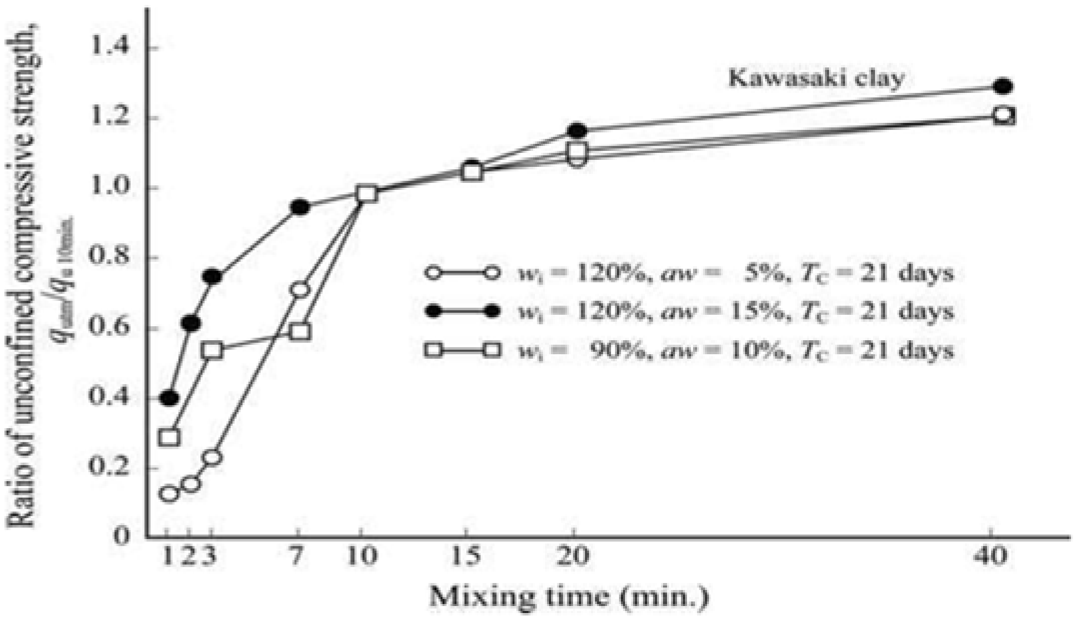

Figure 11.0: Influence of mixing period on unconfined compressive strength, (Terashi et al., 1997)

3.5 Influence of Curing Period

Curing period is another factor that influences the unconfined compressive strength of lime improved soft clay soils as shown in Figure 12.0, (Terashi et al., 1977). This figure shows the influence of curing time (in days) on the unconfined compressive strength of different types of clay improved by quicklime at a constant binder factor of 10% (Terashi et al., 1977). In Figure 12.0, the curing time is plotted in a logarithmic scale along the abscissa while the unconfined compressive strength is plotted on the ordinate. The figure shows that the increase in strength of the improved soil is much dependent upon the type of soil even at constant binder dosage, but the strengths of the improved soils increase almost linearly with logarithm of the curing time.

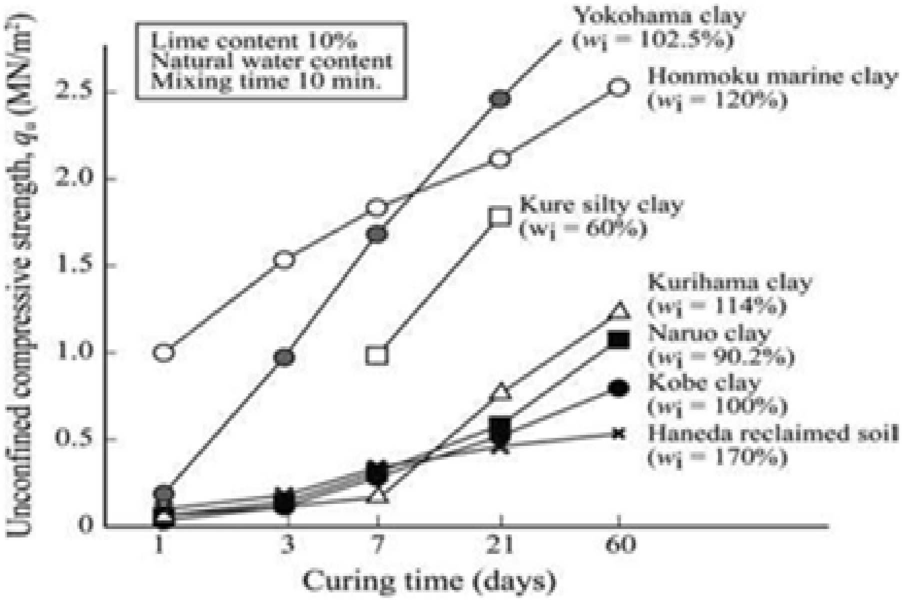

Figure 12.0: Influence of curing period on unconfined compressive strength of quicklime improved soil, (Terashi et al., 1997).

4.0 BEHAVIOUR OF DEEP MIXED COLUMN IMPROVED GROUND

Sukum et al., (2012) investigated the consolidation behaviour of a soil-cement column improved ground using experimental and numerical (PLAXIS 2D) methods. In their laboratory investigation for the preparation of the model ground, soft Bangkok clay was mixed with water up to a water content of about 162%. The model ground was placed in a cylindrical stainless steel mould with diameter and height of 300mm and 450mm respectively and the soil-cement column was installed at the centre of the mould with a 30mm thick sand place at the base of the mould. A vertical consolidation stress of about 20kPa was applied through an acrylic plate with 102mm diameter hole at the middle and 8mm thick, placed on the model composite ground with no horizontal displacement permitted.

The result of their laboratory investigation revealed that the moisture content of the model ground reduces to about 60% and the final settlement of the composite ground is dependent on the stress state. It has also been reported that at larger area replacement ratio (ratio of area of column to area of surrounding soil) that settlement reduces with an accelerated rate of consolidation. Alwi, (2007) reported that the extent of settlement reduction depends not only on area replacement ratio but also on stress concentration ratio (ratio of soil-cement stiffness to that of the surrounding soil).
Ali et al., (2012) carried out a numerical analysis using PLAXIS 3D on settlement of mat foundation on group of cement columns in peat. The analysis of their result revealed that the vertical settlement of peat-cement column decreases as the length of the column increases. Sukum et al., (2012) also observed that the stress on the column reduced due to failure of the soil-cement column and a significant increase in stress on the model ground, leading to an increase in excess pore pressure and the development of cracks on the soil-cement column at failure accelerated the dissipation of the excess pore pressure. According to Soyez et al., (1983) lime columns reduces maximum

embankment settlement up to 50% compared to unimproved soil and an increase in column spacing leads to small reduction in settlement. Holm et al., (1983) carried out a full scale test on lime columns improved soft clay under embankments using 0.5m diameter columns with 1.4m spacing. The improved soft clay has undrained shear strength of 6 to 9kPa and a modulus of compression of about 60 to 175kPa. Their investigation revealed that at an applied load of 50kPa, there was a settlement attenuation of about 50% after 2.6 years.

Carlsten (1996) stated that the diameters of lime and lime cement columns of stabilized clay ranges between 0.5–0.6 m. During lime stabilization, finely milled, burnt lime is mixed with the unimproved soft clay by means of a lime column machine. While in lime-cement columns production, standard Portland cement is added to the lime usually in a proportion of lime/cement of 50/50 percent per weight. The compression modulus and shear strength of lime and lime/cement columns are considerably higher than that of the unimproved clay. He also stated that these columns increase the bearing capacity of the surrounding soft clay depending on the spacing between them.

Yuewen (1996) reported that a deep mixed cement column of 0.5m diameter, 20% cement content and 22% area ratio have been used to improve the bearing capacity of a surrounding soft soil up to 520 to 650kPa and these columns were successfully used to support a 12 to 15 storey building in China. Rogers and Glendinning (1997) attributed the increased bearing capacity of the improved soft clay soils to the strength of the lime columns due to confining pressure provided by unimproved surrounding soil. According to them, such lateral support increases considerably with depth and the degree of vertical confinement of the clay close to the surface determines the method of designing these lime columns.

In a static laboratory and static field tests on the deformation properties of lime-cement column conducted by Massarsch (2005), it was revealed that the modulus of elasticity values obtained from laboratory studies were about 2 to 3 times greater than those obtained from in-situ tests. This shows that the actual long term performance of a lime-cement column still has to be properly investigated because the conditions of the surrounding soil may change over time after installation. According to Massarsch (2005) the modulus of elasticity at 50% of the failure load depends on the unconfined compressive strength of the soil column and this can be expressed mathematically as:

$$\boxed{E_{50} = 160\, q_{u,\,col}}$$

Kivelo (1994) conducted a static field load test on a lime-cement column of 0.5m diameter installed in a soft, plastic clay soil of undrained shear strength of about 18-20kPa and water content of 43%. The mix ratio of lime-cement was 50%. The deformation in the column at varying depth as load increases was measured and the reduction in modulus of elasticity of the column as a function of the imposed load was also measured. It was observed that the reduction in elastic modulus of the column was depended on strain such that an increase in axial strain resulted to a decrease in elastic modulus. The axial strain that will develop in a lime-cement column over time will depend on the interaction of the column with the surrounding soil. Therefore any changes in the properties of the surrounding soil such as change in degree of saturation may affect the long term performance of the column.

Yan, Jie and Gang, (2013) adopted a mechanical and hydraulic coupled 3D finite element analysis approach to study the consolidation behaviour of soft soils fully-penetrated by deep mixed columns. The column and the soft soil were modelled as elastic materials using one quarter of a unit cell due to symmetry. They observed that the consolidation rate increases due to an increase in column modulus, area replacement ratio and permeability of the column. They also stated that an increase in time and column modulus increases the stress concentration ratio and due to interfacial lateral deformation between the column and the surrounding soil, the deformation of the column was not one-dimensional.

It was also stated that settlement of the DMC foundation reduces with larger column modulus and area replacement ratio but increase as soft soil thickness increases. In this study, the interfacial lateral deformation between the column and the surrounding soil was not deeply investigated as the possible changes in the nature of the surrounding soil were not considered.

Tao, Jim and Jing (2014) employed analytical approach to study the consolidation of a composite ground improved with partially penetrated impervious columns. The accuracy of their proposed approach was examined using finite element method and it was observed that the consolidation rate of the composite ground depended highly on the ratio of column length to soil thickness (penetration ratio), such that as this ratio increases, the consolidation rate increases.

Yin and Fang (2006) in their work on the consolidation behaviour of composite foundation consisting of a cement-soil column and unimproved soft marine clay, observed that the excess pore pressure dissipation rate in the soft-cement column was faster than that in improved soft clay due to higher permeability of the soil-cement column and so the soil-cement column acted as a vertical drain. In other words, the soil-cement accelerated the rate of consolidation due to its higher stiffness, resulting to a greater coefficient of consolidation rather than a higher value of coefficient of permeability. Therefore, deep mixed soil-cement column can speed up consolidation process of the composite even at equal values of permeability coefficient between the soil-cement column and the surrounding ground.

Stefan et al. (2012) studied the failure behaviour of soft clay soil improved with lime-cement columns under lateral loading condition using single and overlapping column patterns. There experimental work was carried out in a shear box as shown in Figure 2.16, (Stefan et al. (2012), where the columns were installed in laboratory prepared clay. In their numerical studies, the soft clay was modelled using the Drucker-Prager model, while the DMC(s) were simulated using the damage plasticity model.

According to Stefan et al. (2012), the damage plasticity model was adopted to simulate the failure mechanism of the improved soil due to irreversible plastic and damage deformation during loading. They manufactured the laboratory clay by mixing kaolin soil with water up to 90% water content and the clay slurry was poured into a 0.9m high circular steel box with a diameter of 0.5m as shown in Figure 13.0. They tested the unimproved clay, 12 single DMC(s) and two rows of six DMC(s) each and each column having 500mm length and the overlaps between columns in the two rows were varied in three steps. A movable steel plate with a sealing plastic film was then placed on top of the slurry and the steel box sealed at the top with a massive steel plate. The slurry was consolidated with a 50 mm thick drainage sand layer placed at the bottom of the box to achieve a 95% degree of consolidation. Stefan et al. (2012) adopted the dry deep mixing technique using a binder that consisted of 30% quicklime and 70% Portland limestone cement respectively.

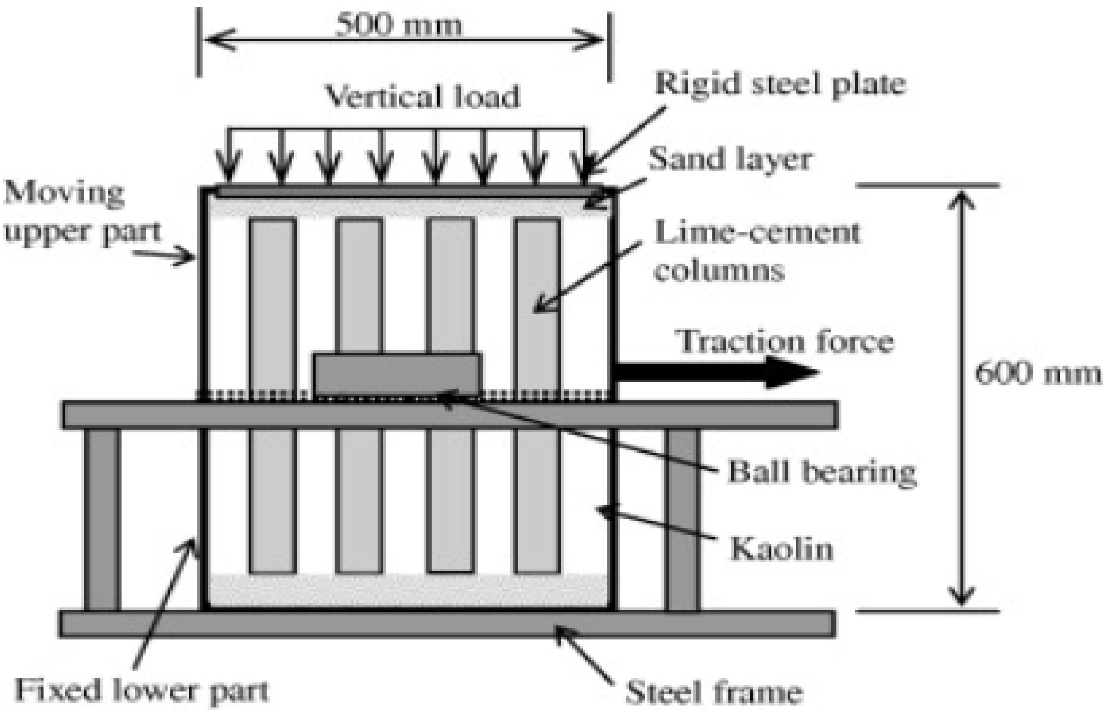

Figure 13.0: Schematic of the Shear Box Test, (Stefan et al. (2012)

The top half of the box was free to move laterally. Steel weights were used to apply lateral traction force which was increased in stages. The result of their study revealed that the single columns failed due to bending, and there was progressive cracks initiated by the columns furthest away from the centre, in the direction of the imposed load. Their study also revealed a significant increase in shear resistance for the columns installed in rows due to higher bending resistance. They also, stated that failure was due to a combination of shear and bending and there was a reduction in tensile strength of the column in the overlap zone, which gave rise to a reduction in shear resistance and the failure becomes a bending failure.

Stefan et al. (2012) observed that the model tests and the numerical analyses indicated that, it is most likely that shear resistance is being overestimate in the current design practice where only shear failure is considered. It has been investigated that the main failure mechanisms were captured in the damage plasticity model up to a very reasonable extent. Stefan et al. (2012) claims that under small deformations, rows of columns will provide a higher shear resistance than single columns. This is a clear fact because columns still possesses higher flexural resistance after induced cracking in the rows of columns. They concluded that the overlapping zones between the lime-cement columns have an influence on the shear resistance. According to Stefan et al. (2012) the finite element analyses showed the complex failure mechanisms of a lime-cement column but this was not investigated in their study, therefore creates gap for further investigation.

Dennes and Glen (2005) carried out a case history of full-scale deep mixing improved soft clay ground supporting a 6.0 m high reinforced test embankment. The deep mixed columns were installed in the soft clay using the jet mixing technique and the cement slurry was injected at a pressure of 20 MPa and excess pore pressure build up during installation was monitored. They compared with another test embankment of approximately the same height constructed previously on surrounding unimproved soft clay foundation. They also monitored settlements as well as the lateral movement during and after the embankment construction. The result of their analysis revealed that deep mixing columns effectively reduced the settlement by almost 70%, while lateral movement of the foundation soil was reduced by about 80%. The local differential settlement between the deep mixing columns and the unimproved surrounding soil amounted to about 8–20% of the average total settlement of the improved ground, and this could induce downdrag skin friction on the deep mixed columns.

4.1 Deep Mixed Column under Embankment Loading

Paulo, Joao and Antonio (2011), carried out a numerical analysis study on an embankment built on a normally consolidated soft soil reinforced with deep mixing columns using a coupled soil-water formulation. They adopted the modified Cam Clay model concerned with Biot's consolidation theory to simulate the soil behaviour using a two dimensional FE code developed at the university of Coimbra. The DMC was modelled using linear elastic laws with parameters based on laboratory results.

Kitazume (2009) reported that linear elastic laws do not allow yielding of top of the DMC to be simulated due to low confining stress and high loads, and the failure due to bending caused by horizontal movement of the column that may occur at the columns founded under the toe of the embankments. But, Abusharar, Zheng, and Chen (2009), stated that linear elastic model could be adopted because the reduction in strength properties using safety factors causes stress level to be considerably lower than the yielding stress of the DMC material.

Paulo, Joao and Antonio (2011), revealed that the application of DMC to strengthen the foundation of an embankment structure, reduces settlement and small differential settlement. They also found that with the use of DMC, consolidation was reduced because higher stiffness of the column is associated with greater coefficient of consolidation. An increase in young's modulus of the DMC reduces settlement and consolidation time irrespective of the higher vertical effective stresses on the DMC. Their results also revealed that in both mechanical and hydraulic terms, the behaviour of the **soil-DMC** system is wholly controlled by the properties of the column. Sari et al. (2009) adopted a finite element modelling approach to study the consolidation behaviour of an embankment supported by multi columns of cement-fly ash- gravel, soil-cement and lime columns as shown in Figure 14.0, (Sari et al. 2009). They modelled the embankment fill and the surrounding soil as linear elastic-perfectly plastic materials with the Mohr-Coulomb failure criterion and the multi-columns as linear elastic materials. The result of their analysis showed that soft ground treated with multi-columns can reasonably reduce total and differential settlement and restricts lateral movement of the supported embankment, thereby increasing its stability.

Comparing their numerical results with field test result, they observed that the embankment settlement was more prominent at the centre than at the toe of the embankment and that the long term stability of the embankment is enhanced by the cement-fly ash-gravel-lime column due to its higher compression modulus. This study has revealed that the long term stability of an embankment can be enhanced by deep mixed multi-columns due to its high compression modulus. At the long term, there is a possibility that the moisture content of the surrounding soil might change due to seasonal fluctuation of soil moisture. But the study has not incorporated the possible effect of this change of degree of saturation of the surrounding (change in moisture content) on the long term performance of this column.

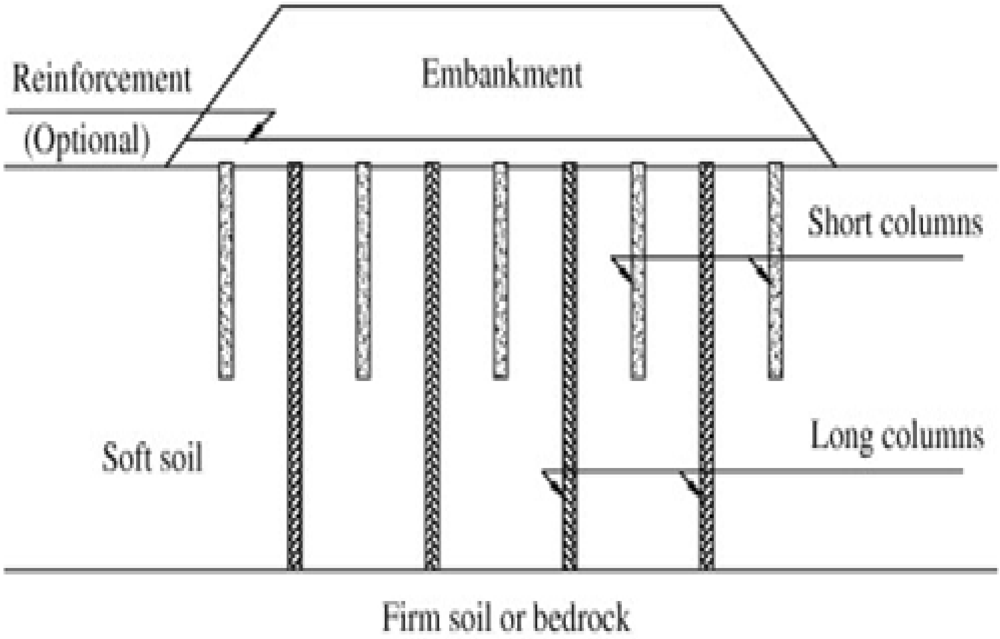

Figure 14.0: A multi-column supported embankment, (Sari et al. 2009).

Paulo, Joao and Antonio (2011) observed that when the permeability of the deep mix column exceeds the permeability of the virgin soil, the deep mix soil behave like a vertical drain controlling the entire water flow of the soil-deep soil column system.

According to Seksun et al. (2012), when the ratio of the permeability of the improved soil and the surrounding soil equals unity, the soil-cement column will not act as a drain and because the yield stress and the stiffness of the improved ground is enhanced by the soil-cement column, the improved soil goes into over consolidation state under the influence of the applied vertical stress. Also, water flow occurs entirely in the soil when the permeability of the soil exceeds that of the deep mix column and the column drains horizontally to the soil.

They concluded that the consolidation time of the soil-deep mix column depends on permeability and stiffness of the deep mix column. How this consolidation time will be affected by time varying loading will also be considered in this research. This study has not considered the long term performance of the deep mix column in mitigating the embankment settlement. It has been based on parametric studies and therefore, creates gap for further research studies.

Song –Yu et al (2012) carried out a field investigation to study the performance of a T-shaped DMC, supporting an embankment over a soft ground. They conducted several field tests on a high way embankment built on a soft clayey soil supported by a T-shaped deep mixed columns (TDMC) and the conventional DMC. In situ and laboratory studies such as vane shear and piezocone penetration tests were included in the study. The test site was divided into three different sites, which they referred to as site A, B and site C and each site having a width of 50m and length of 100m respectively. The strengths of sites A and B were improved using a T- shaped deep mixed column while site C was improved using the conventional deep mixed column, serving as the control section. Figure 15.0, Song –Yu et al (2012) shows the columns arrangements with the corresponding spacing (S), lengths (L) and diameters (D) at each site.

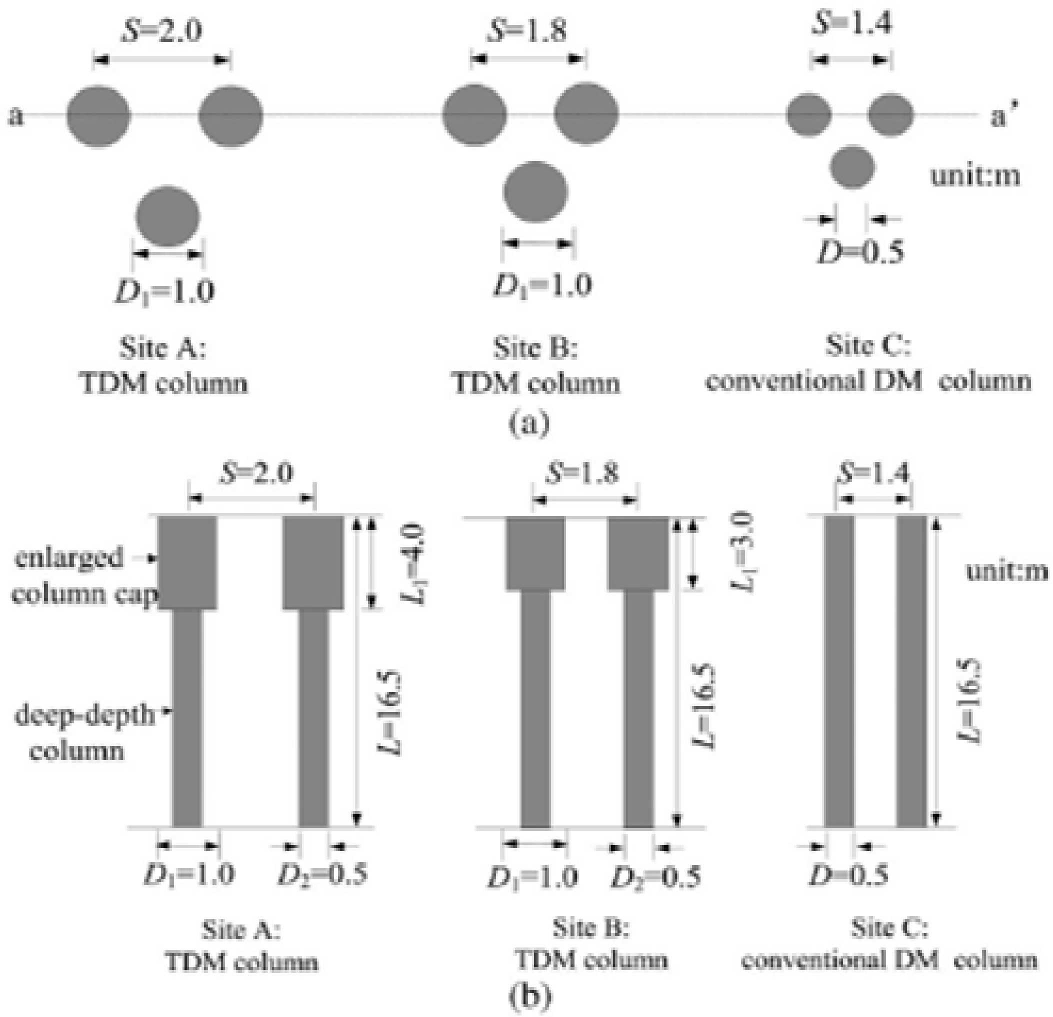

Figure 15.0: Geometry of Columns at Different Test Sites, (Song –Yu et al 2012).

They adopted a water-cement ratio of 0.55 and a cement dosage rate of 255kg/m^3 for the production of the soil columns, slightly above the cement dosage rate of 5% - 16% of the weight of untreated soil recommended by Winterkorn and Fang (1975).

They reported that during column installations, the cement slurry was injected at a pressure of 30Mpa and a maintained rotational speed of 60rpm. The installed columns were then subjected to static plate load test 28 days after installation with a sand mat of 100mm thickness placed between the soil columns and loading plates before loads were applied. The T- shaped deep mixed columns have larger diameter at shallow depths compared to their diameters at deeper depths. Loads were applied with increment ranged from 20 to 30 kPa and maintained until two consecutive readings less than 0.1mm in each hour was obtained.

Song –Yu et al (2012) stated that prior to the filling of the embankment, a monitoring section was selected at the centre of each test site and instruments such as earth pressure cells, piezometers and inclinometers were located at the monitoring section as show in Figure 16.0.

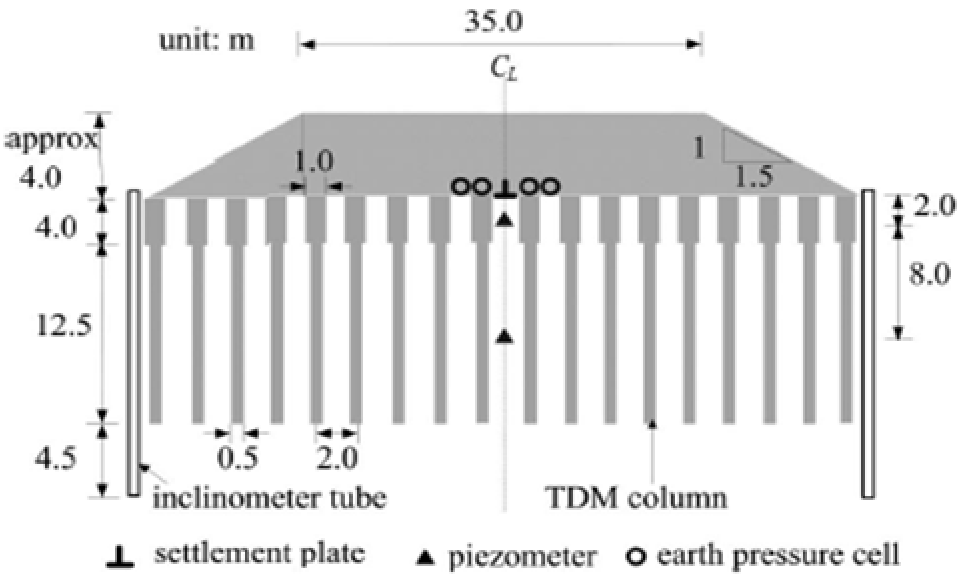

Figure 16.0: Location of Monitoring Instruments at Site A, (Song –Yu et al 2012).

The result of their investigation revealed that the T- shaped deep mixed columns installed at sites A and B resulted in cement savings by weight up to about 15 and 7% and also, save in construction time of about 28 and 19% compared with that of the conventional deep mixed column at the control section (site C). It was revealed that the bearing capacities of the T-shaped deep mixed columns placed at sites A and B were found to be greater than the bearing capacity of the conventional deep mixed column. This implies that T-shaped deep mixed columns have the tendency of yielding stiffer foundations than the conventional deep mixed columns in shallow supported ground.

They also, stated that the conventional deep mixed column exhibited a higher stress concentration ratio than the T-shaped deep mixed column supported ground but the efficacy of the T-shaped deep mixed column supported ground was higher than that of the conventional deep mixed column. It was also reported that the T-shaped deep mixed column supported ground performed better in terms of settlement than the conventional deep mixed column because it gave lesser settlement values at sites A and B. Song-Yu (2012) concluded that the use of T-shaped deep mixed columns for ground improvement under embankment loading conditions provided a viable, economic and technological sound solution but, they have not considered the effect of changes in strength and modulus of elasticity on the long term performance of both the T-Shaped and the conventional DMC that may occur due to change in loading orientation during and after construction of the embankment.

5.0 CONCLUSION

The essence of ground improvement is to enhance the engineering properties of weak soils to provide stability and sufficient bearing capacity for construction purposes. In deep soil mixing, the amount of binder to be mixed with the weak soil depends on the initial moisture content of the surrounding soil. Several researchers have reported on this method of soil improvement through laboratory experiments, in situ testing and numerical modelling. Most literatures reviewed in this study have shown that research on deep soil mixing had focused on the mechanical properties of the improved soil. Such as the compressive strength, stiffness, modulus of elasticity and consolidation behaviour of the improved ground. For example, Ali et al., (2012), Lin and Wong, 1999, Fang et al., (2001), Porbaha et al., (2001), Yin, (2001), Porbaha, (2002), Farouk and Shahien (2013), Tao, Jim and Jing, 2014) etc.Others focused on the effect of soil type, binder type, binder content, water-cement ratio and area replacement ratio on the mechanical properties of the improved ground, for example; Nur et al. (2013), Terashi et al., (1977), Kitazume and Terashi, (2012), Farouk and Shahien, (2013) etc. In all these studies, the interaction of the improved soil columns with the surrounding weak soil after installation has received little or no attention. Especially, with the possibility of a change in the degree of saturation of the surrounding soil over time due to environmental changes.It is most likely that the strength, stiffness and the resistance to shear deformation of the improved material might change over time, and these might impair the long term performance of the improved soil columns in terms of interfacial behavioural mechanism.

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