# REVITALISATION OF ORGANIC AND PEAT SOILS

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# ABSTRACT

Ground improvement projects are often necessary and site – specific to ensure project success. The author hypothesizes that problematic soil, which are often mass replaced can be revitalised with modest proportions (<10%) of Ordinary Portland Cement as a binder to make a positive contribution to economic, green engineering, and resource sustainability. Deep cement mixing (DCM) techniques have proved to be successful worldwide and use large proportions (circa 200%) of cement, lime and/or fly ash in dry or wet mixing to form in-situ piles with enhanced strength and stiffness in comparatively short time. Revitalisation of organic and peat soils is not a practice currently adopted in Malaysia which has a distribution of over 1.5 million ha of such challenging soils. Such soils have high water and organic content and their mechanical chemical and biological properties degenerate with time. Land shortage for development promotes land reclamation. The shear strength and stiffness behaviour of these heavily organic soils and the revitalised soils is central to this research study. Peat soil from Pontian, Johor and an organic soil from Bukit Rambai, Malacca are investigated with laboratory controlled cement slurry mixing at water cement ratios of 3.5,7,14,140 for peat and 5,10,15 for organic soil. Specimens of these soil mixtures were prepared in polyvinyl chloride tubes (50 mm diameter 300 mm long) and cured at room temperature of $25^{o}$C and relative humidity of 50% for 7,14 and 28 days. Unconfined compressive strength, consolidated undrained triaxial, bender element, and one dimensional consolidation tests were done to assess the strength and stiffness improvements of the 'revitalised soils'. Increases of up to 30% and 16% in unconfined compressive strength and 229% and 0.9% in $G_o$ for Pontian Peat and Malacca organic soil respectively are reported in this study.

**Keywords:** cement slurry, organic soils, peat soils, revitalisation, strength, stiffness.

# ABSTRAK

Projek pembaikan tanah sering diperlukan dan tapak - khusus bagi memastikan kejayaan projek. Penulis menghipotesis bahawa tanah bermasalah, yang sering digantikan atau ditambak boleh digiatkan semula dengan hanya menggunakan simen (OPC) dalam kadar yang sederhana (<10%). Simen bertindak sebagai pengikat yang mana juga boleh memberi sumbangan positif kepada ekonomi, kejuruteraan hijau, dan kelestarian sumber. Teknik ‘Campuran Simen Dalam (DCM) telah terbukti kejayaannya di seluruh dunia. Sebahagian besar (sekitar 200%) simen, kapur dan abu terbang samaada dalam bancuhan kering atau basah digunakan untuk membentuk cerucuk di tapak untuk meningkatkan kekuatan dan kekukuhan tapak dalam jangka masa yang pendek. “Proses mengiat semula” tanah organik dan tanah gambut bukan merupakan satu amalan biasa di negara Malaysia yang mana tanah yang mencabar ini meliputi 1.5 juta hektar. Tanah tersebut mengandungi kuantiti air dan organik yang tinggi dan ciri- ciri mekanik, kimia dan biologi merosot mengikut masa. Kekurangan tanah untuk pembangunan menggalakan teknik penambakan tanah. Kelakuan kekuatan ricih dan kekakuan tanah berorganik tinggi dan tanah digiat semula ini adalah penting dalam kajian penyelidikan ini. Tanah gambut dari Pontian, Johor dan tanah organik dari Bukit Rambai, Melaka digunakan dalam kajian ini. Bancuhan basah simen pada nisbah air simen 3.5, 7, 14, 140 untuk tanah gambut Pontian, manakala nisbah air simen 5,10,15 untuk tanah organik digunakan. Spesimen kajian telah disediakan dalam tiub polyvinyl chloride (PVC) (bergaris pusat 50 mm dan 300 mm panjang) dan diletakkan dalam kotak pada suhu bilik 25$^{o}$C dan kelembapan bandingan 50% untuk jangka masa 7, 14 dan 28 hari. Ujikaji kekuatan mampatan tak terkurung, ujian pengukuhan tak tersalir, elemen bender dan pengukuhan telah dijalankan untuk mengkaji pembaikan kekuatan dan kekakuan tanah yang digiat semula. Peningkatan kekuatan tak terkurung masing –masing sebanyak 30% dan 16% dan sebanyak 229% dan 0.9% $G_o$ untuk tanah gambut Pontian dan tanah organik Melaka telah dilaporkan pada kajian ini.

**Kata kunci**: Simen buburan, tanah organik, tanah gambut, proses mengiat semula, kekuatan, kekakuan.

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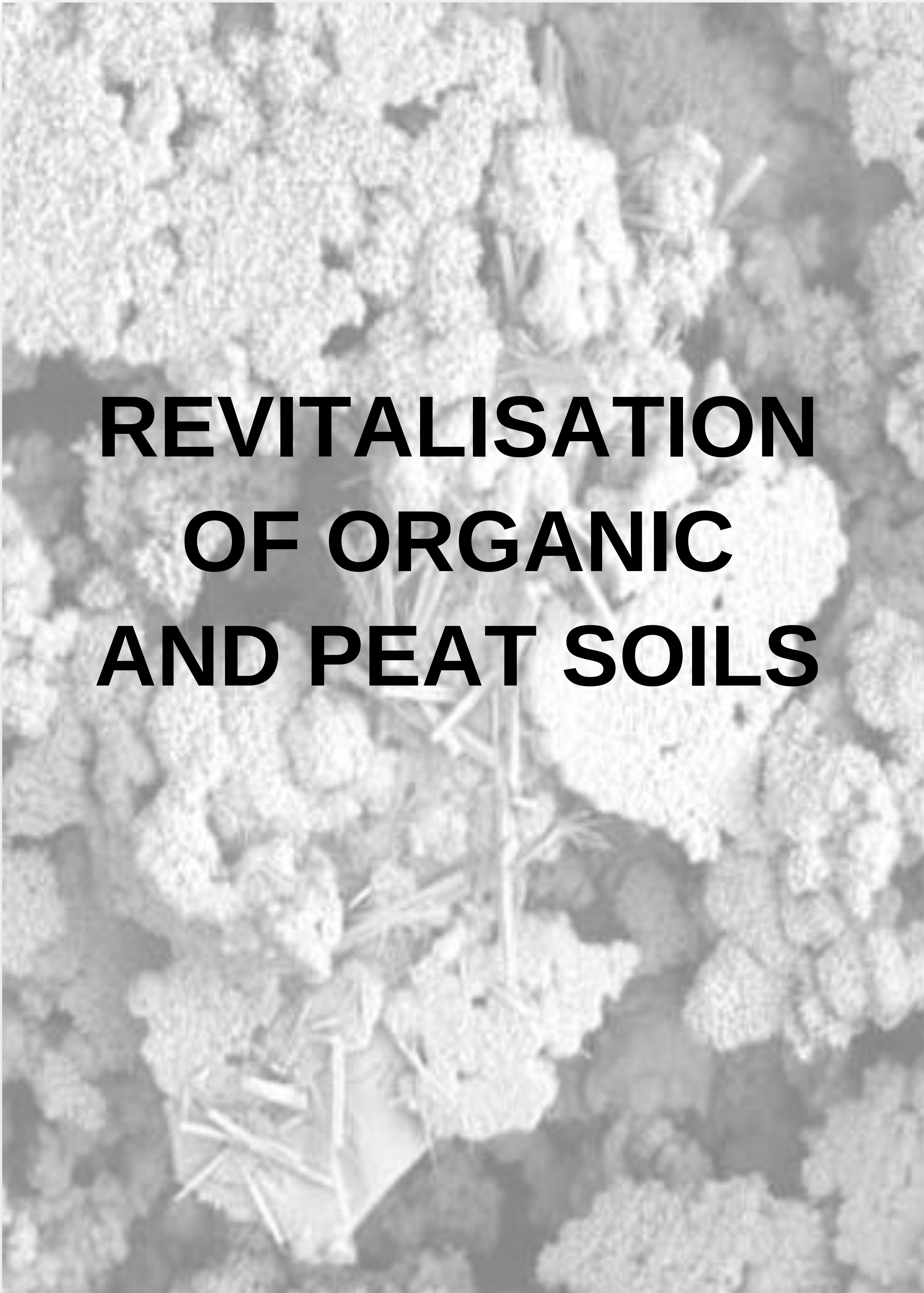
## LIST OF NOTATIONS AND ABBREVIATIONS

| | |
|---|---|
| a | binder factor |
| $Al_2O_3$ | aluminium oxide |
| $a_w$ | binder content |
| ASTM | American Society for Testing and Materials International Standard |
| A | Skempton A parameter |
| B | saturation ratio (Skempton) |
| BE | bender element |
| BS | British standard |
| $^oC$ | degree celsius |
| CaO | calcium oxide |
| $C_c$ | compression index |
| Cc | coefficient of curvature |
| $Ca^+$ | Calcium |
| CH | calcium hydroxide |
| CSH | Calcium silicate hydroxide |
| CAH | Calcium aluminate hydroxide |
| $C_3S$ | Tricalcium silicate |
| $C_2S$ | Dicalcium silicate |
| $C_3A$ | Tricalcium aluminate |
| $C_4AF$ | Tetracalcium aliminoferrite |
| Cl | chlorine |
| $COO^-$ | carboxylic acid |
| $C_r$ | recompression index |
| $C_s$ | swelling index |
| $C_u$ | uniformity coefficient |
| $C_g$ | coefficient of gradation |
| CU | consolidated undrained triaxial |
| d | day |
| $D_n$ | grain diameter at n percent finer diameter |
| DCM | Deep cement mixing |
| e | void ratio |
| e.g. | for example |
| et al. | and other people |
| E | young modulus |
| ET | ettringite |
| $Fe_2O_3$ | feric oxide |
| FTIR | fourier transform infrared spectroscopy |
| g | gravity |
| $G_o$ | small strain shear modulus |
| $G_s$ | specific gravity |
| HCl | hydrogen chloride |
| HF | hydrogen fluoride |
| $HNO_3$ | nitric acid |

| | |
|---|---|
| i.e. | that is |
| LL | liquid limit |
| log | logarithm |
| M | original organic soil |
| MARDI | *Malaysian Agricultural Research and Development Institute* |
| MID-IR | Mid- Infrared (Majority of FTIR applications) |
| Mn | organic soil with n percent of cement |
| MOS | Malacca organic soil |
| $m_v$ | coefficient of volume change |
| N | standard penetration resistance |
| NA | not available |
| OC | organic carbon |
| OPC | ordinary Portland cement |
| P | original peat soil |
| pH | a measurement of the acid or alkaline level |
| PI | plasticity index |
| PL | plastic limit |
| Pn | peat soil with n percent of cement |
| ppm | parts-per-million, $10^{-6}$ |
| PP | Pontian peat |
| PVC | polyvinyl chloride |
| RECESS | Research Centre for Soft Soil |
| RM | Ringgit Malaysia |
| SEM | scanning electron micrograph |
| $SiO_2$ | silica dioxide |
| $SO_3$ | sulfur trioxide |
| SPT | standard penetration test |
| Sr | degree of saturation |
| TOC | total organic carbon |
| UCS | unconfined compressive strength |
| USCS | unified soil classification systems |
| UTHM | Universiti Tun Hussein Onn Malaysia |
| V | volume |
| $V_p$ | compression wave velocity |
| $V_s$ | shear wave velocity |
| XRD | X- ray diffraction |
| XRF | X-Ray fluorescence |
| w | water content |
| $w_i$ | initial water content |
| $W_T$ | weight of soil |
| $W_B$ | weight of binder |
| $W_s$ | dry weight of soil |
| w:c | water cement ratio |
| $u_b$ | back pressure |
| ZnO | zinc oxide |
| $\gamma$ | Unit weight |
| kPa | pressure |

# LIST OF APPENDICES

# REVITALISATION OF ORGANIC AND PEAT SOILS



# CHAPTER 1
# INTRODUCTION

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## 1.1 Research context and problem statement

Tropical peat lands occur throughout the tropics. However in Malaysia alone there is about 1.54 million hectares, of which about 13 % are in peninsular Malaysia, over 80 % in Sarawak and about 5 % in Sabah (Ongkili, 2005; Leete, 2006). Peat or highly organic soils present a problematic and poor quality soil due to it's excessive compressibility, poor drainage on site (Edil, 2003; Wong et al., 2008). It is very difficult to stabilise peat due to it's very high water content and as it consists of decomposed plant fragment, lower pH and as a result it's potential to interfere chemically and biologically with time and environmental condition (Magnan, 1993; Hernandez et al., 2009). These unfavourable characteristics of peat soil deposits make them unsuitable for supporting most engineering projects or infrastructure development. Furthermore, such ground presents failure due to ground instability such as localised sinking and extreme settlement over extended time periods when subjected to a increase in loading (Jarret, 1995; Huat et al., 2004).

Common remedial practice in such instances involves mass replacement with imported materials, deep piling, installation of vertical drains, thermal precompression, laying surface reinforcement as geotextile and chemical admixture applied either as deep insitu mixing or surface stabiliser (Edil, 2003). Where possible engineers seek to avoid building on these problematic ground. Nevertheless, increasing land use makes it a growing necessity to build on these unfavourable grounds. Developing the knowledge of their geotechnical properties such as shear strength, stiffness and compressibility behaviour is needed to provide suitable design parameters for this type of ground before any construction can take place on them.

Deep mixing method relies on the introduction of a chemical binder to alter the physical properties of the soil mass. Through this process, the soil will be improved by the reduction of water content, cement hydration hardening, bonding of soil particles and filling of void by pozzolanic reaction (CDIT, 2002; Yee et al., 2007; Hebib et al., 2003).

This application was started in the late 1970's in Japan and Sweden by adding dry or wet binders in order to reduce settlements, and improve the stability and strength of soil; increase of bearing capacity, prevention of sliding failure, reduction of vibration and remediation of contaminated ground (Terashi et al., 1979; Kawasaki et al., 1981; Ahenberg et al., 1995). Due to the success of deep mixing technique worldwide, there have been various novel construction and installation technologies such as adding binders to stabilised peat and organic soils. This technique is widely adopted because it is more appropriate in term of construction and the ground can be improved very quickly (Hayashi et al., 2005). Furthermore the technique has proved to be a successful application leading to possible offers of economical design in terms of raw material and being less labour intensive. The technique also causes minimal disturbance during installation in terms of noise and vibration levels. In addition, deep mixing method is a reliable solution applicable to a wide range of soils. Hence it provides excellent quality improvement due to uniform and homogenous product quality which is controllable by counter – rotation mechanism comparison with other ground improvement methods (Hampton et al., 1998; EuroSoilStab, 2002).

Typical chemical binders used in soil stabilisation include cement, lime, fly ash or waste industrial material as stabilized agents, essentially to modify the original soil texture and properties to a stronger soil matrix (Ahnberg et al., 2005; Duraisamy, 2007; Hebib et al., 2003). As suggested by Broms (1986), in Southeast Asia, it is preferable to use cement instead of lime, because of the low cost of cement compared to lime and the greater strength which can be obtained with cement in a shorter period. Chen (2006) reported that cementatious compounds can change the composition and structure of the calcium liberated gel to form insoluble calcium humid acid, which is responsible for the increase in soil strength.

The strength of soil mixtures are influenced by various parameters like original soil character, binder type, binder dosage rate and proportion, binder water cement ratio, uniformity of soil binder mixing, specimen preparation techniques, and curing condition (Dong et al., 1996; Shen et al., 2005; Al- Tabba et al., 1999; Bhadriraju et al., 2008). Accurate estimation of laboratory mix design for selecting optimum stabiliser dosage and proportions is thus important for successful field implementation of deep mixing method. Hence, quality assessments of laboratory stabilised soil design should be considered to ensure that strength and stiffness properties are able to meet targeted properties established and thus contribute to quality control with in situ implementation.

Previous research (Den Haan, 1997; Axelsson et al., 2002; EuroSoilStab, 2002; Janz et al., 2002; Hernandez et al., 2009) has described correlations between strength, stiffness and compressibility behaviour of peaty soil which help assess the effectiveness of using cement as stabilising agents at a particular site. This research study addresses the influence of binder amount with various water/cement ratios. As a preliminary effort it also attempts to consider parameters such as socio-economic, health-related and environmental friendliness of the method. The project presents a wide diversity of knowledge and experience in term of technology and expertise which is able to help engineers solve such problematic ground pragmatically for long term applications. The flow chart for this research is shown in Figure 1.1 and discussed research methodology in Chapter 3.

## 1.2 Aim and objectives of study

### 1.2.1 Aim

The aim of the study was to investigate the suitability of using cement as a means of revitalising peat and organic soils.

### 1.2.2 Objective

The objectives of this study are consequently as given below:

1. To determine geotechnical (i.e. compressibility, shear strength and stiffness) and chemical (i.e. pH) properties of revitalised organic and peat soils.
2. To investigate the effectiveness of cement as a binder on the strength and stiffness characteristic of revitalised soil.
3. To characterise the behaviour and observe the microstructure of organic/peat soils.

## 1.3 Research scopes

The scope of this study is to focus only on the geotechnical properties of cement revitalised peat and organic soils. Organic soils were obtained from Bukit Rambai, Malacca (MOS). Peat tested from MARDI Pontian (PP), Johor. Both disturbed soft soils were obtained at depth of about 1.5m from surface level. Ordinary Portland cement was added to PP and MOS samples at water cement ratios of 3.5, 7, 14, 140 % and 5, 10, 15 %, respectively. Relevant physical properties measured were natural water content, particle size distribution, Atterberg limits, specific gravity, organic content, ash content, fiber content and acidity according to BS 1377:1990 and ASTM, D4427.

Laboratory soil samples are prepared for simulating the mixing method. Unconfined compressive strength, bender element, consolidated undrained triaxial and one dimensional consolidation (an odeometer) tests on 7, 14 and 28 day curing samples were conducted to assess the stabilized soil properties.

‘Curing’ in this study means placing the specimens in a closed box with raised platforms at room temperature (25$^{o}$C). The box is filled with bleach solution during the curing period. The study also adopts a practical approach to addressing the effectiveness of using cement as stabilising agents in terms of strength, stiffness and compressibility. In addition, Scanning Electron Miscroscope (SEM) studies made were to observe any changes in microstructure within the revitalised soils.

## 1.4 Outline of thesis

The organization of the thesis is as shown below:

| Chapter | Titles | Description |
|---|---|---|
| 01 | Introduction | Project introduction including aim, objective and scopes of study |
| 02 | Literature review | Reviews the literature relating to the research, which includes soil properties/ characteristics, binder properties, soil stabilisation technique, and laboratory testing theories. |
| 03 | Research methodology | Materials and experimental work in terms of sample preparation, test equipment, and procedure is described. This section discusses a developed laboratory testing technique which is considered necessary in the site for successful field implementation. This chapter attempts to provide insights into the knowledge for improving (revitalising) peaty ground. |
| 04 | Laboratory investigation | Present and analyse the test results, where soil classification, mineralogy, changes in microstructure of stabilised soils, shear strength, compressibility index and stiffness of soil are discussed in detail. |
| 05 | Discussion and correlation | Correlations between the various parameters are established and compared with results from previous researchers. |
| 06 | Conclusion and recommendation | Outlines a summary of present work and detail recommendation for future work based on current research experience and literature review. This helped to establish a new method for further practical and long term applications. |
| | References | A complete list of references is included |
| | Appendices | Appendices of relevant topics can be found in the end of the thesis. |

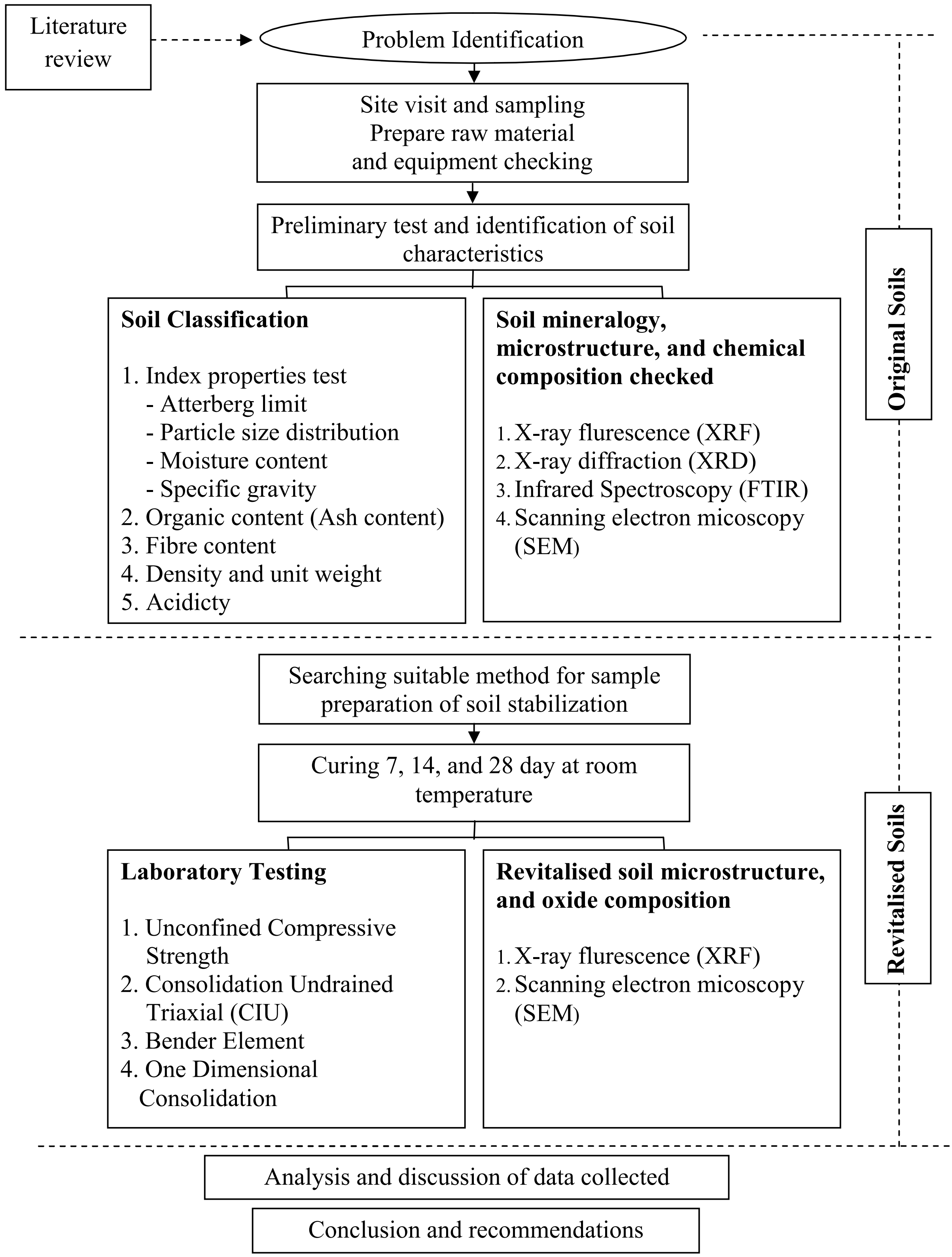


**Figure 1.1: Flow chart of the study**

# CHAPTER 2
# REVIEW OF PAST RESEARCH ON SOIL REVITALISATION

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## 2.1 Introduction and definitions

This chapter presents the author's critical review of research relevant to the study. Over three months of the postgraduate study period was devoted to literature search where over one hundred relevant papers from journals and thesis were downloaded, collated and studied. At the outset of this chapter it is desirable and noteworthy to point out the difference in the generic definitions, particularly of "stabilisation" and "revitalisation".

Stabilisation is defined in the Dictionary of Civil Engineering terms as a result of the increased strength and other properties such as improved bearing capacity of the foundation for the structure. Soil stabilisation is widely used to support the construction of industrial buildings; improve the stability of embankments for roads; preventing landslides; preventing sinking shafts and reduce settlements. Soil stabilisation is achieved by injecting cementing materials or chemical solutions into the ground (EuroSoilStab, 2002). The basic methods of soil stabilisation are cementation, argillisation, bituminisation, silicification, resinification methods using electrochemical or thermal action, and artificial freezing (Farlex).

Cement stabilisation has been and is an appealing approach by virtue of the cementation and hence the improvement of the soil strength. Revitalisation , on the other hand, is defined as a process to make something that is weak become strong and successful bringing again into activity and prominence (Cambridge Advanced Learner's dictionary, 2003). This is synonymous to the process in the medical field of increasing the vitality of a person's health and ability that has degenerated due to aging or other health reasons. In the context of this study, the organic content in both peat and organic soil is in a state of dynamic degeneration due to its decomposition. The properties of these can degenerate to such a level that will make the soil be classed as problematic and challenging. The engineers would often opt for the easy path of "mass displacement" causing an associated "environmental hazard". This study proposes to investigate the prospect of revitalising such poor displaced material via slurry mixing for landfilling in reclamation projects.

## 2.2 Soft soil – definition and review

Most classification systems divide soils into three main groups: coarse, fine and organic. The main and characteristic differences in these groups are as shown in Table 2.1.

**Table 2.1: Major classes of engineering soils (Source: adopted from Whitlow, 2001)**

| | Coarse | Fine | Organic |
|---|---|---|---|
| Inclusive soil types | Boulders<br>Gravel<br>Sand | Silt<br>Clay | Peats |
| Particle shape | Rounded to angular | Flaky | Fibrous/Hemic |
| Particle or grain size | Coarse | Fine | - |
| Porosity or void ratio | Low | High | High |
| Permeability | High | Low to very low | Variable |
| Apparent cohesion | None to very low | High | Low |
| Interparticle friction | High | Low | None to low |
| Plasticity | None | Low to high | Low to moderate |
| Compressibility | Very low | Moderate to high | Usually very high |
| Rate of compression | Immediate | Moderate to low | Moderate to rapid |

The rapid pace of infrastructure development in most countries compels engineers to be prepared to be able to design and construct on all types of soils including the weaker organics in an economical and challenging manner. A soft soil is one that can be moulded easily with finger pressure and having an undrained shear strength in the range 20 to 40 kN/m$^2$ (Barnes, 2000).

### 2.2.1 Peat soil – definitions, and Malaysian perspective

The definition of peat is not unique but depends on the purpose or the field of application. The standard definitions are given in Table 2.2.

**Table 2.2: General definitions of peat (Zainorabidin, 2010)**

| Purpose of application | Definition | From reference |
|---|---|---|
| Geotechnical engineering | All soils with organic content greater than 75% are known as peat. Soils that have organic content below 75% are known as organic soils. | ASTM D4427 – 92 |
| Agriculture | Peat is classified if the organic content is more than 20%. | USDA (Soil Taxonomy) |
| Soil science | All soils with organic content greater than 35% is categorized as peat. | USDA (Soil Taxonomy) |

In the South East Asia region, Malaysia, is second to Indonesia, in the abundance of peat ground. It has a total of 2.13 million hectares of peatlands in the states of Selangor, Johor, Perak, Pahang, Sabah and Sarawak, with the largest area of more than 1.5 million hectares in Sarawak (Ongkili, 2005). Figure 2.1 show the peat distribution around South East Asia.

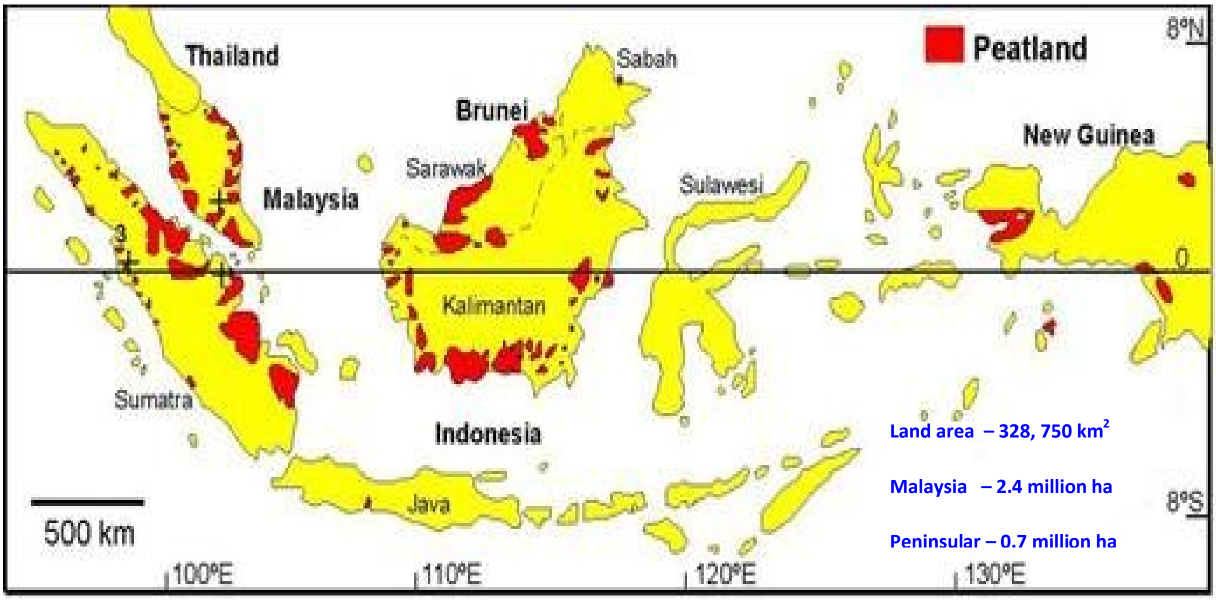



**Figure 2.1: Distribution of peatlands in SE Asia. (Source: Rieley et al., 1996)**

Peat is brownish-black in color and in its natural state is composed of 90% water and 10% solid material. Partially decomposed organic matter accumulates over thousands of years due to the lack of oxygen under waterlogged conditions that promotes the formation of peat a soil defined as containing at least 65% organic matter (Soper et al., 1922; Radforth, 1969; Babel, 1975; Stanek et al., 1983; Moore, 1989; Van der Heijden et al., 1994). Forests formed on these peat soils are called peat swamp forests. Huat, 2004; Edil, 2003; Den Haan, 1997; Jarret, 1995; Landva, 1980 have all reported that the behaviour of the peat found in different geographical areas differ from one another because of the type and origin of the organic matter, emphasising the need for careful geotechnical characterisation. They possess unique vegetation assemblages adapting to the high degree of water logging, low pH and low available nutrient conditions such that the properties of peat can change greatly across a deposit, and even within short distances particularly in fibrous peat (Frank, 2006; Mamit, 2009). In a tropical country, such as Malaysia, most peat lands belong to basin peats. It forms “peat domes”, up to 10-15 m high and are usually found in the lower stretches of major river courses, and mangroves along coastal areas.

Tropical lowland peatlands are normally formed between rivers in low-lying coastal areas or flood plains where periodic flooding occurs. Peat swamps occur inland just beyond coastal mangroves and often spread over some 3 km to 5 km on the floodplain of rivers. They are characterised by an 8 m to 20 m thick layer of peat, which is mainly semi-decayed plant material accumulated over some 8,000 years. Peat soil generally originates from plant/ animal remains (Zainorabidin and Wijeyesekera, 2007). Peat formation occurs when the rate of accumulation of organic material exceeds the rate of decomposition. The build-up of layers of peat and degree of decomposition depend principally on the local composition of the peat and the degree of waterlogging (as shown in Figure 2.2). Peat formed in very wet conditions accumulates considerably faster and is less decomposed than peat accumulating in drier places (Leete, 2006). As long as the peaty soil is saturated with water, the swamp ecosystem is in balance. Peat swamps are like sponges that absorb and soak up excessive rain and river water, thus controlling floods during the rainy season and releasing much needed water supplies during the dry season.

Peatlands have many direct and indirect uses and functions, over and above the role they play in controlling global warming. They are a habitat for many animals and are very important for reducing flood peaks and for maintaining base flows in rivers during dry periods. Tropical peat lands occur throughout the tropics. Peatlands are a globally significant store of carbon and thus an important player in the fight to control global warming. Although they only cover 3% of the land surface, they store between 20-35% of carbon present on the world's land surface (Chee et al, 2007). In fact, peatlands are one of the very few mature ecosystems that can actively accumalate carbon in the long term.

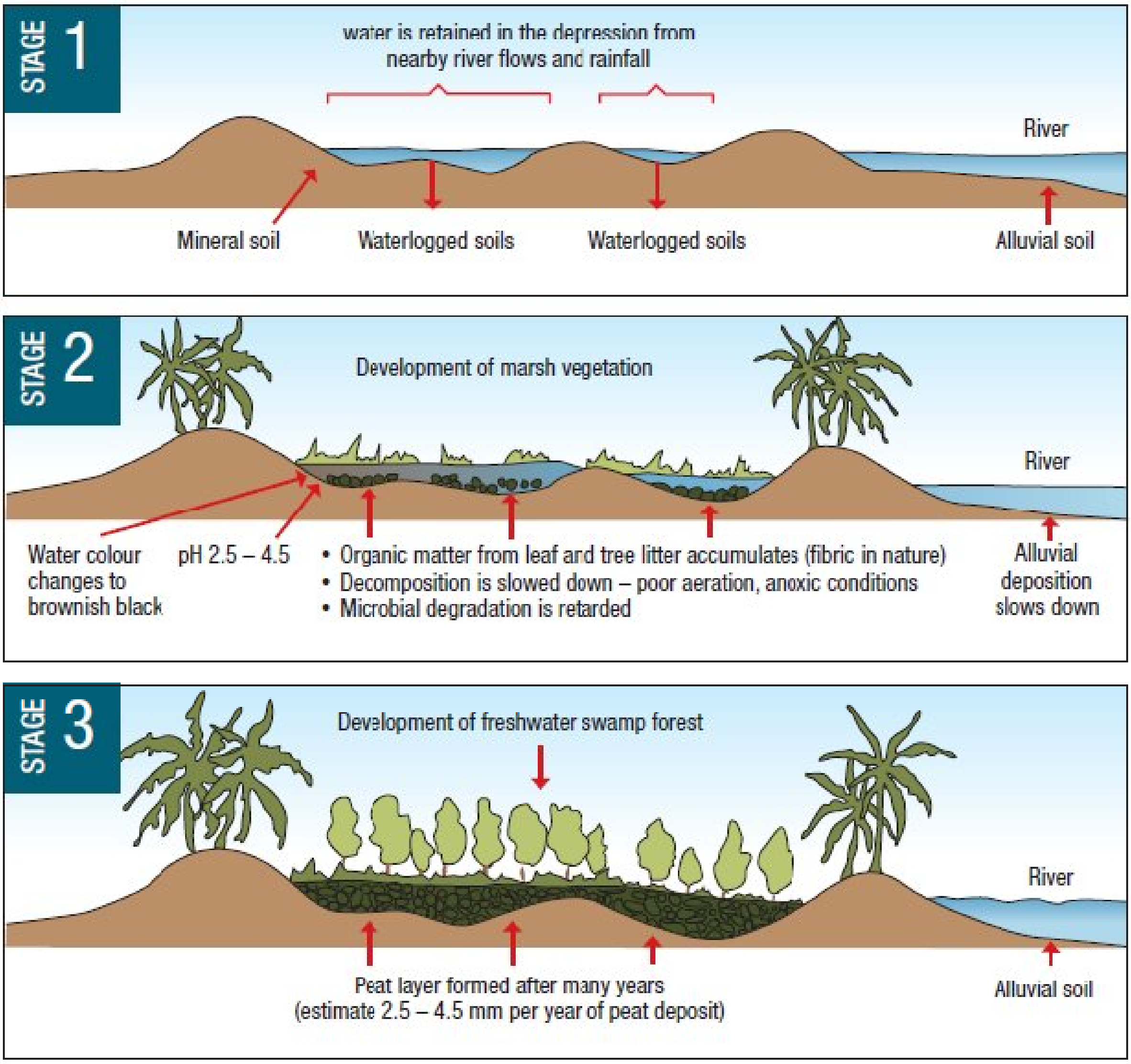
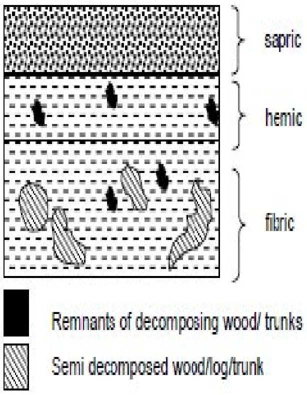


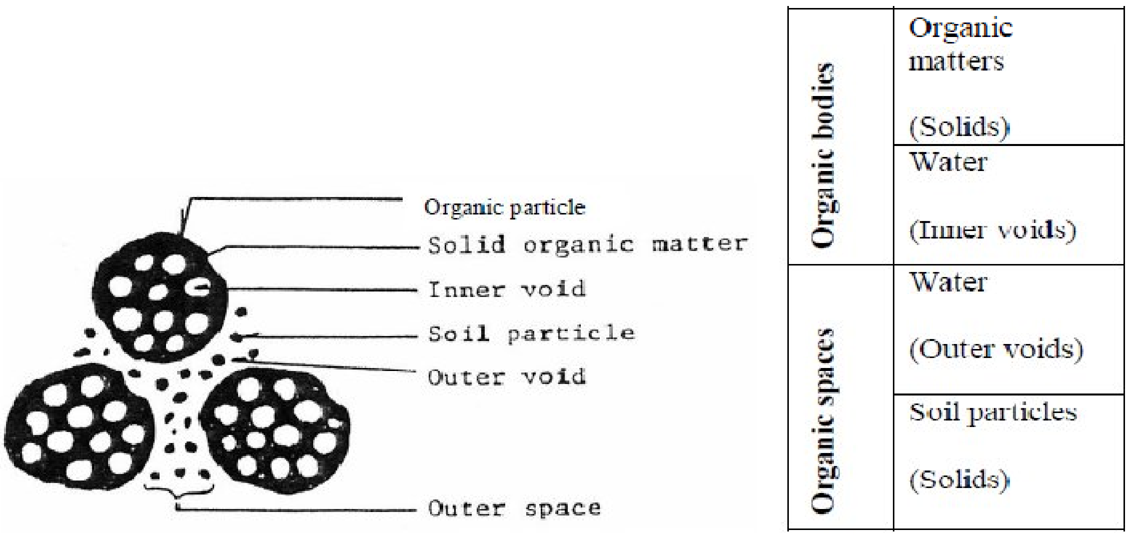

**Figure 2.2: Peat swamp formation (Source: Leete, 2006)**

Most peat classifications focus the fiber content together with the Von Post scale. Farnham and Finney (1965) define three main categories: fibrous, hemic and amorphous peat (Table 2.3). Fibrous peat is a mixture of fragmented organic material formed in wetlands under appropriate climatic and topographic conditions. Dhowian and Edil (1980) further stated that if peat has 20% fiber content or more, then it can be classified as fibrous peat. Figure 2.3 show a cross section of the peat or the schematic diagram of deposition of fibrous peat deposit. According to Karlsson and Hansbo (1981), fibrous peat differs from amorphous peat in that it has a low degree of decomposition, fibrous structure, and easily recognizable plant structure. The compressibility of fibrous peat is very high and so it's rate of consolidation. It's fabric is defined as > 0.15 mm structure and the degree of humification of organic matter is commonly measured in the field using the 10 point scale (H1–H10) of Von Post method (1922). It also describes the consistency and colour of the peat. Kivinen (1980) classified peat based on a combination of botanical factors (moss, sedge, wood), degree of decomposition, and the status of the nutrients. This definition has an agricultural perspective and is applied to limited thickness zones. Ash content is a further factor used in classifying peat deposits. The low end of ash content (or equal to 100 minus organic content) defines peat and the higher end is for organic soils. Pontian peat (PP) tested in this study was therefore categorised as hemic peat (33 to 66% fiber content).

Peat or highly organic soils represent problematic soils and poor quality of soils due to limited compressible index to support man made structure as shown in Figure 2.4 (a) and (b) (Edil, 2003; Wong et al., 2008; Hebib and Farell, 2003). Organic soils and peat are most difficult to stabilise due to lower solid content, high porosity, high water holding capacity, irreversible shrinkage low pH and its potential to change chemically and biologically with time and environmental condition (Huat, 2002; Hernandez and Al-Tabbaa, 2009; Wahyunto et al, 2010). Although this is a major breakthrough, much more needs to be done before any technological improvement in the construction on peat ground can be achieved. Trend for technological innovations will continue and have a strong impact on efforts to reduce the settlement rate of structures on peat foundations.

**Table 2.3: Classification of peat based on the Von Post scale and fibre content (Source adapted by Jarret, 1995)**

| Designation | Profile morphology of drained organic soil (Source: Mutalib et al. 1992) | Group | Description | Fibre content (%) |
|---|---|---|---|---|
| Sapric /Amorphous |  | H8-H10 | • Sapric/ Amorphous | <33% |
| Hemic / Moderately Decomposed | | H5-H7 | • Intermediate degree of decomposition | 33-66 |
| Fibrous peat | | H1-H4 | • Low degree of decomposition.<br>• Easily recognized plant structure, primarily of white masses | > 66 |




(a) (b)

**Figure 2.3: (a) Schematic diagram of deposition of fibrous peat deposit, (b) Schematic diagram of multi-phase system of fibrous peat (Source: Kogure *et al.*,1993)**

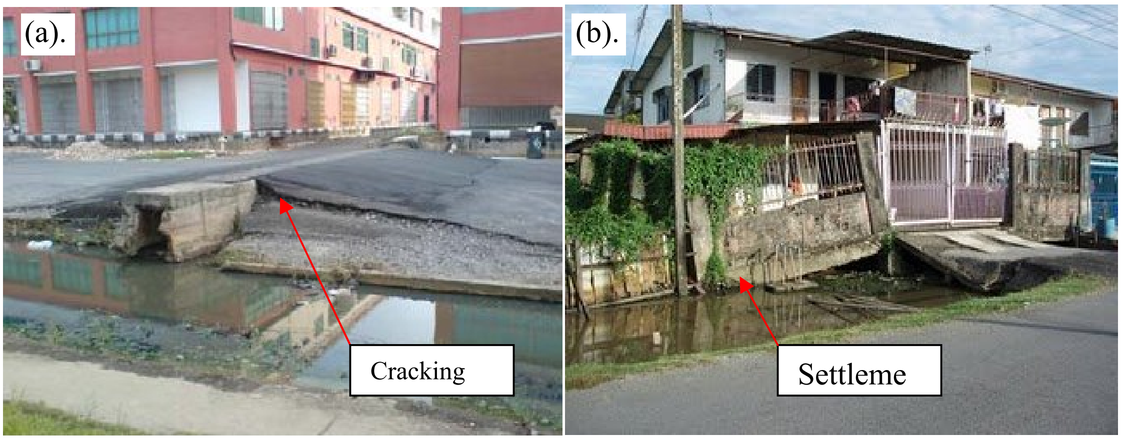



**Figure 2.4: (a) Ground settlement caused poor drainage and road system in a commercial lot, Sibu.; (b) Housing area on low –lying peat soil ground, Jalan Lai Chee, Sibu (Source: Kolay et al, 2011)**

### 2.2.2 Organic soil

The soils will be called ‘organic soil’ once their organic content exceeds 20% of their dry mass. Organic soil is comprised of peat or fine, coarse, or very coarse soil with an organic content. Organic soils can be distinguished from inorganic soil by their grey, dark grey or black colour and their distinctive odour which can be enhanced by gentle heating. This soil commonly occurs by the coastline, lakes, bays, estuaries, harbours and reservoirs. The presence of organic matter tends to make the soil smoother to the touch. Soil organic matter is composed of many parts, such as (Plank, 2001).

- intact plant and animal tissues and microorganisms;
- dead roots and other recognisable plant residues; and
- a mixture of complex amorphous and colloidal organic substances no longer identifiable as plant tissues.

Soil humus or humic material makes up 60 to 80% of the organic matter in soil; humus is a complex system of substances remaining in the soil after extensive chemical and biological breakdown of fresh plant and animal residues (Plank, 2001). The other 20 - 40% organic matter is less stable and partially decomposed. Humus is stable and relatively resistant to microbial attack; it is responsible for the cation exchange capacity (CEC) of organic matter and can be divided into three groups (Brady et al., 1999):

- Fulvic acid- low molecular weight, light color, soluble in both acid and alkali, and most susceptible to microbial attack. Depending on conditions, the half-life (time it takes to destroy half of the material) is approximately 10 - 15 years.
- Humic acid- moderate molecular weight and color, soluble in alkali but insoluble in acid, and intermediate in degradation potential with a half-life >100 years.
- Humin- high molecular weight, dark color, insoluble in acid and alkali, and most resistant to microbial attack.

Soil content of humic and fulvic acids vary by depth, climate, and geography (Thurman, 1985). Tindall et al. (1999) reported that fulvic acid soils with significant amounts of aluminum, iron, and organic matter have been mobilized and transported deeper into the profile. Podzols evaluated by Clare et al. (1954) also showed variations in organic matter content. They concluded that “active” organic matter is formed in the vegetable top-soil and subsequently leached by rainwater. The Malacca organic soil (MOS) used in this study is brownish in colour with some fine sand and decayed wood (described later in section 3.2.1). Table 2.4 shows the physical properties of peat and organic soil.

## 2.3 Overview of binders

Typical chemical binders used commonly in soil stabilisation of organic soils and clay slightly in peat (Ahnberg et al., 2005; Duraisamy et al., 2007) are cement and lime. Cement is a hydraulic binder. Setting of cement will enclose soil as a glue but it will not change the structure of soil. CSH and $Ca(OH)_2$ is produced as reaction products of cement reacting with water.

Cement was used as the binder in this research because of its low cost; ease of storage in a hot and humid climate such as Malaysia. The price comparison given in Table 2.5 is based on the purchase price per kilogram of the binders all around Malaysia.

**Table 2.4: The physical properties of peat and organic soil**

| Soil type/ Characteristics | | Moisture content | Von post class | Fibre content | Organic content | Linear shrinkage | Consistency limit | | pH | Specific gravity |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | LL | PL | | |
| | | % | | % | % | % | % | % | | |
| Peat soils | Matang , Sarawak (Kolay et al, 2011) | 600 | H4 | 79 | 91 | 5 | 200 | - | 3.8 | 1.2 |
| | West Malaysia peat (Huat, 2002; Zainorabidin et al, 2003; Duraisamy et al, 2009; Kalantari et al, 2009) | 200-700 | H4-H8 | 31-77 | 65-92 | - | 190-360 | 100-200 | - | 1.2-1.7 |
| | East Malaysia peat (Huat, 2002; Chan, 2009; Tang, 2009) | 200-2207 | - | - | 76-98 | - | 210-550 | 125-297 | 3-7.2 | 1.1-1.6 |
| | Klang, Selangor (Wong et al. 2008; Deboucha, 2009; Hashim et al, 2008) | 414-850 | H4 | 85- 90 | 89- 98 | 5.6 | 174 | 58 | 3.5-4.6 | 0.9- 1.4 |
| Organic soils | West Malaysia coast clay | 70-140 | - | - | - | - | 56-90 | 30-35 | - | - |
| | East Malaysia coast clay (Huat, 2002) | 36-73 | - | - | - | - | - | - | - | - |

In the most general sense of the word, cement is a binder, a substance that sets and hardens independently, and can bind other materials together. Cement is made by heating limestone with small quantities of other materials (such as clay) to 1450°C in a kiln. The resulting hard substance, called 'clinker', is then ground with a small amount of gypsum into a powder to make 'Ordinary Portland Cement', the most commonly used type of cement (often referred to as OPC). Portland cement is a basic ingredient of concrete, mortar and most non-specialty grout. Portland cement may be gray or white (Zakaria, 2001). The main chemical compounds of Portland cement are shown in Table 2.6. The main properties of Portland cement is shown in Table 2.7 (Jackson, 1996). There are numerous different type of cement. Standard specification for Portland cement (ASTM C 150), recognise eight basic types of Portland cement concrete.

**Table 2.5: Comparison marked price per kilogram between lime and cement in Malaysia**

| Description/Year | Cement | Lime |
|---|---|---|
| 2005 | RM0.204 | RM0.80 |
| 2006 | RM0.228 | RM1.20 |
| 2007 | RM0.27 | RM1.20 |
| 2008 | RM0.27 | RM1.50 |
| 2009 | RM0.286 | RM1.80 |
| 2010 | RM0.32 | RM1.80 |

**Table 2.6: Main chemical compounds of Portland cement (Source: Jackson, 1996)**

| Name of compound | Chemical composition | Usual abbreviation | Description |
|---|---|---|---|
| Tricalcium silicate | $3CaO.SiO_2$ | $C_3S$ | Hydrates and hardens rapidly and is largely responsible for initial set and early strength. Portland cements with higher percentages of $C_3S$ will exhibit higher early strength. |
| Dicalcium silicate | $2CaO.SiO_2$ | $C_2S$ | Hydrates and hardens slowly and is largely responsible for strength increases beyond one week. |
| Tricalcium aluminate | $3CaO.Al_2O_3$ | $C_3A$ | Hydrates and hardens the quickest. Liberates a large amount of heat almost immediately and contributes somewhat to early strength. Gypsum is added to portland cement to retard $C_3A$ hydration. Without gypsum, $C_3A$ hydration would cause portland cement to set almost immediately after adding water. |
| Tetracalcium aliminoferrite | $4CaO.Al_2O_3.Fe_2O_3$ | $C_4AF$ | Hydrates rapidly but contributes very little to strength. Its use allows lower kiln temperatures in portland cement manufacturing. Most portland cement color effects are due to $C_4AF$. |

**Table 2.7: ASTM types of Portland cement (Source: ASTM C150)**

| Type | Name | Purpose |
|---|---|---|
| I | Normal | General-purpose cement suitable for most purposes. |
| IA | Normal-Air Entraining | An air-entraining modification of Type I. |
| II | Moderate Sulfate Resistance | Used as a precaution against moderate sulfate attack. It will usually generate less heat at a slower rate than Type I cement. |
| IIA | Moderate Sulfate Resistance-Air Entraining | An air-entraining modification of Type II. |
| III | High Early Strength | Used when high early strength is needed. It is has more $C_3S$ than Type I cement and has been ground finer to provide a higher surface-to-volume ratio, both of which speed hydration. Strength gain is double that of Type I cement in the first 24 hours. |
| IIIA | High Early Strength-Air Entraining | An air-entraining modification of Type III. |
| IV | Low Heat of Hydration | Used when hydration heat must be minimized in large volume applications such as gravity dams. Contains about half the $C_3S$ and $C_3A$ and double the $C_2S$ of Type I cement. |
| V | High Sulfate Resistance | Used as a precaution against severe sulfate action - principally where soils or groundwaters have a high sulfate content. It gains strength at a slower rate than Type I cement. High sulfate resistance is attributable to low $C_3A$ content. |

Bergado et al., (1996) noted there are two major chemical reactions in cement stabilisation which is primary hydration reaction of cement and water and secondary pozzolanic reaction between cement and soil mineral. The hydration reaction leads to initial gain in strength because of the formation of cementation products by drying up of the water. Furthermore pozzolanic reaction, which is also termed as solidification will harden soil skeleton with increase in strength at times. When Portland cement is mixed with water its chemical compound constituents undergo a series of chemical reactions that cause it to harden (or set). When using cement, which contains large amounts of calcium oxide (denoted C), hydration will occur as the cement comes into contact with the pore water in the soil, resulting in the formation of calcium hydroxide (denoted CH). Some of this calcium hydroxide will be absorbed into the soil particles. Ion exchange will take place and the soil will be modified into a somewhat drier and coarser structure due to the slaking process and flocculation of the clay particles that take place (Boardman et al., 2001; Saitoh et al., 1985). The calcium hydroxide is not consumed in this process and is free to react with the silica and alumina contained in minerals present in the soil. These reactions, termed pozzolanic reactions, will result in the formation of calcium silicate hydroxide (CSH) and/or calcium aluminate hydroxide (CAH) (TRB, 1987). The reaction which take place in soil- cement stabilisation is as represented in equation 2.1 – 2.4.

$C_3S + H_2O \rightarrow C_3S_2H_X$ (hydrated gel) + $Ca(OH)_2$ ----- (2.1)

Primary cementitious products

$Ca(OH)_2 \rightarrow Ca^{++} + 2(OH)^-$ ----- (2.2)

$Ca^{++} + 2(OH)^- + SiO_2$ (Soil silica) $\rightarrow$ CSH ----- (2.3)

Secondary cementitious product

$Ca^{++} + 2(OH)^- + Al_2O_3$(Soil alumina) $\rightarrow$ CAH ---- (2.4)

Secondary cementitious product

The reactions given here are for tricalcium silicate ($C_3S$) only, because they are the most important constituents of Portland cement. Cement also is generally used to adjust soil acidity, as well as to improve the physical condition of the soil (Mohamed et al., 2002). The pozzolanic reaction increases the pH of pore water due to the dissolution of the hydrated lime and the strong base dissolves soil silica and alumina from clay minerals

(Umesha et al., 2009). Mohamed et al., (2002) report that soil acidity was found to be high due to decomposition rate, the lower the pH, the greater the decomposition rate.

Soil cementing has a green aspect by blending the existing soil with Portland cement onsite. This is an inexpensive and great environmental technique to repair an area that needs to be matched to an existing grade.

## 2.4 Generic stabilisation methods

Constructing structures on peaty ground involves the risk of ground failure and extreme and undesirable settlements occur when subjected to loading over extended periods of time even though costly construction method such as deep piling, installation of vertical drains, thermal precompression, laying surface reinforcement are adopted. It is however becoming necessary to develop special methods for peaty ground due to the increasing demand for the development of such land use. Edil (2003) and Huat (2004) summarise a number of construction options that can be applied to peat as shown in Table 2.8.

Deep cement mixing (DCM) is used as the methodology being researched for these problems in this study. Two main components of DCM serve the following functions; Increase shear strength of soil, reduce permeability of soil. Cement binder in slurry form was added to the soft soil. As the binders hardens, the improved soil mass has higher strength and increased stiffness. The technique is adopted because it can improve ground considerably in a short period of time (Hayashi et al., 2005). The research has been directed toward the utilisation of cheap and readily available local materials to solve the peaty ground problems. Figure 2.5 show the deep cement mixing application in-situ.

**Table 2.8: Common construction option on peat and high organic ground**

**(Source: Edil, 2003 and Huat, 2004)**

| Methods | | Description | Advantage | Disadvantage |
|---|---|---|---|---|
| Avoidance | | Changing the construction location. | Less failure risk | Lack of land make this not always possible. |
| Excavation (displacement/ replacement) | | Replace the poor soil by excavation or by dumpling suitable imported fill materials. Practical typically up to 5m depth | Easy, common used | Cost, mass consuming, high risk of failure, larger impact on environment |
| Ground improvement | Surface reinforcement, preloading and vertical drain | Geotextile, geogrids, timber or bamboo mattressesbeing placed to increase the overall stability of the embankment. Used to overcome problems of instability in fills constructed over weak deposits. Takes time but can be accelerated by use of vertical drains and stability can be enhanced by geosynthetic reinforcement. Loading can be achieved by placement of load on the surface or vacuum consolidation. | Cheaper, improve bearing capacity | Time consuming, larger settlement during serviceability, |
| | Deep/ chemical stabilisation | Forced mixing of lime or cement deposits to form stabilized soil column. | Economic, flexibility, saving energy and materials. | Time need for curing, limit possiblity to increase stability |
| | Pile support | Fundemental means of construction over all soft soil. The structural forces to a competent layer, to avoided largely settlement | Expensive. | Fast method, significantly with the settlement of the surrounding area. |
| Lighweight fill | | Utilize light material to cope with extreme soils. | Minimizing the settlement. Reused wasted material. | Less strength support |

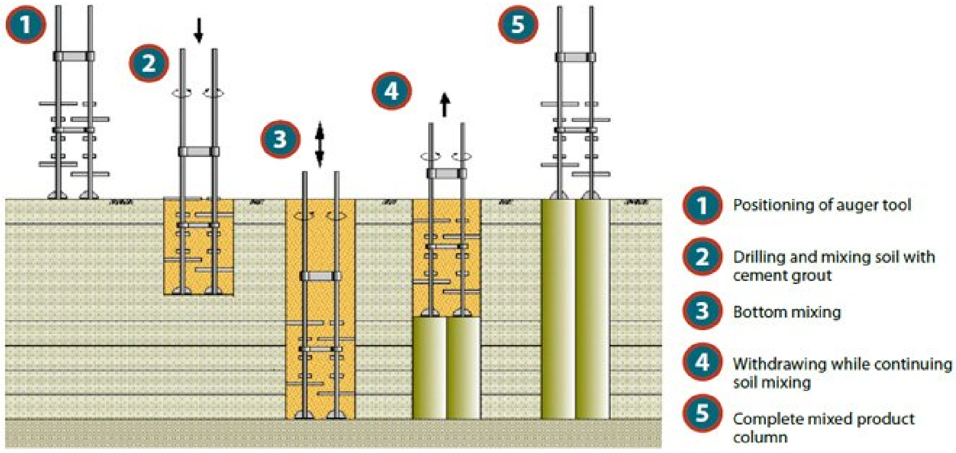



**Figure 2.5: Deep cement method application in-situ**

**(Source:*http://www.geofirmllc.com/groundimprovement.html*, 2010)**

Curing temperature, period, relative humidity, and curing environment are the major environmental soil conditions that influence the strength of treated soil (Enami et al., 1991; Babasaki et al., 1996, Lorenao et al., 2004). The binder water ratio is another important factor that affects the degree of improvement of the treated soils. (Bergado et al., 2005; Pathivada, 2005). If not properly designed, this method could lead to poor mixing in the field thereby affecting the effectiveness of the deep soil mixing. When using a custom made field mixing equipment, factors such as the shape of mixing blade, rotational speed, and velocity of penetration and retrieval of auger impact the properties of treated (Shen et al., 2003).

In many parts of the world soft subsoil is a very serious problem for maritime construction. For these situations, in-situ soil cement deep mixing is often implemented. As most of the developed areas are located near to the coastline, one of the options to create more land is to reclaim coastal areas. The term “land reclamation” is used to describe two different activities. In the first sense, land reclamation involves modifying wetlands or waterways to convert them into usable land, usually for the purpose of development. Land reclamation can also be a process in which damaged land is restored to its natural state. The practice of filling in wetlands and waterways to make more land is ancient. Humans tend to settle near water, since they need water to survive, and because waterways can be used as a method of transportation for people and goods. As human settlements grow, the pressure on the existing land also grows, and people may start to expand outwards by filling in the surrounding area.

Reclamation of coastal land meets problems such as instability of the reclaimed platform and long term excessive settlement. The basis of all these mixing systems is that cement hardener is first mixed with water in slurry form, which is then injected into the soil by high pressure pumps. Simultaneously, full depth reclamation with cement is a process of recycling the old pavement by grinding it into the soil and blending in a certain percentage of Portland cement into the mixture. The cement reacts with the pore water of the soil, resulting in an in-situ hardening process (Andrews et al., 2005). Full depth reclamation is a green application. There is no need to haul off the old material to the land fill. In this way, the soil is improved reviatalised in specific locations and to the standards required in the shortest time and in an economical manner. The stabilized soil will be stronger, more uniform and more water resistant, resulting in a long low-maintenance life.

## 2.5 Revitalisation

In this research, revitalisation give importance on land reuse to restore the soil properties appropriately for popularize new trade. The proposal for the "Revitalisation on peaty ground" forecast an effective low cost margin protection system using local available technology and resources. This is to balance the need both economically and culturally requirement.

The revitalised lands are commonly reused for community development or green space projects. A part of cultural particles aimed at the reconstruction of the mother nature was the considerate reused sites originally with high concern of environment and social equality (Vavricek1 et al., 2006). Indeed, many sustainable technologies, methods, and strategies implemented for land development. The subsequent total felling of these stands create conditions for the use of heavy-duty machinery for the preparation of sites. In the course of large- scale scarification the top – soil horizons moved, which causes marked degradation of the soil environment (Vavricek1 et al., 2010). This is considered seriously in peat ground, where peatland known as a globally significant store of carbon and thus an important player in the fight to control global warming (Chee et al., 2007). This will cause a land pollution disaster, nutritional degradation and wasteful. Since the beginnings of the environment are effect, methods of fertilization have been an important measure of prevention and remediation of soil degradation. The present revitalization of the soil environment is based on the principle of spreading these men – made (Laar, 2004).

## 2.6 Laboratory sample preparation

Due to the success of the deep mixing methods in different subgrade related site conditions, several new method have evolved and were labeled with various terminologies based on their geographical locations (Japan, Denmark, Swedan, Finland, Norway, United States, and others) (Porbaha, 2000). The differences in test procedures and definitions of parameters involved in DCM practice complicate the laboratory simulation procedure by presenting several additional variables. Hence, there is a need to develop a generalised laboratory testing protocol to incorporate several deep mixing process related and parameters. However, it should be noted that the test procedure developed should be considered as site specific owing to the fact that the expansive soils exhibit seasonal moisture content, which may alter the required amount of molding water to optimize the binder proportion needed in field. A part of an on – going research conducted in this context provided an opportunity to accomplish the study need.

An extensive literature review was performed to understand the various terms used in the current practice. Based on the previous studies (Ahnberg et al., 1994; Matsuo et al., 1996; Miura et al., 1998; Japanese Geotechnical Society, 2000; EuroSoilStab, 2002; Jacobson et al., 2003; Francisco, 2003; Lorenzo et al., 2004; Filz et al., 2005; Horpibulsuk et al., 2005), a brief summary of various standard practices for laboratory simulation of deep soil mixing is presented in Table 2.9. The table show major difference among the various laboratory simulation procedures which summarised the duration of mixing, sample preparation procedure prior to treatment. The proportion rate of the binders is usually expressed in weight per bulk of the soil to be treated and typically represents 6 to 12% by dry weight of soil (Jacobson et al., 2003; Bruce, 2001). For instance, a binder quantity of 150 to 250 kg/m$^3$ is recommended for peat and 100 to 200 kg/m$^3$ for gyttja

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