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SEDIMENTATION AND CONSOLIDATION BEHAVIOUR OF FLY ASH-BASED GEOPOLYMER STABILISED DREDGED MUD

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(Civil Engineering)

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Dedications

This work is dedicated to the soul of my late father – Hajj Hurry Jaditager (1931 – 2013) who was keen to see the results of this research study, however, dad's time was over, and he couldn't make it to see the completion of my research study. Also, I dedicate this work to the soul my late brother - Amir (1973 -1990) who departed so early.

Abstract

Ports conduct maintenance and capital dredging campaigns to maintain channel depths, improve navigational safety of vessels, and to cater for larger ships with deeper draughts**.** Most of the soft dredged material derived from these dredging campaigns is beneficially used as a fill material for land reclamation purposes. Port authorities undertake land reclamation works to address land scarcity and environmental constraints that are associated with dredged material placement alternatives.

Land reclaimed with soft dredged mud has geotechnical challenges of slow self-weight consolidation, high compressibility and low bearing capacity. To overcome these geotechnical challenges and to alleviate risk of structures settlement, dredged material stabilisation techniques such as chemical admixtures, electrokinetic, stone columns, prefabricated vertical drains (PVDs), and surcharging are implemented.

For these existing dredged material stabilisation methods to be applicable, the land reclamation fill material must have settled, consolidated and gained sufficient strength and stiffness to be traversed by ground improvement plant and workforce. By then, the reclaimed (the man-made) ground becomes similar to a naturally formed soft ground that civil and geotechnical engineers have no control on its soft soil formation processes. On dredging and land reclamation with soft dredged mud slurry project site, dredge cutters and drag heads rip and disintegrate marine sediment turning it into high water content dredged mud slurry. Then, the dredged mud slurry is pumped into land reclamation containment ponds to settle and self-weight consolidate to form soft land reclamation fill material.

The dredged mud slurry takes several hours from the moment it is placed into containment ponds to the commencement of the land reclamation fill material formation. This time slot is sufficient for an early geotechnical intervention to stabilise the dredged mud while it is still in its slurry stage, prior to the formation of the soft land reclamation fill material. Stabilising the soft dredged mud slurry provides an opportunity to manipulate its sedimentation behaviour that controls microstructure, consolidation and compressibility characteristics of the resulting land reclamation fill material.

This research study has investigated feasibility of stabilising 400% water content dredged mud slurry that is derived from Port of Townsville, Queensland Australia, using fly ash-based geopolymer binder at 6%, 12% and 18% by weight. The fly ash-based geopolymer binder is chosen for its tolerance to high water content nature of the dredged mud slurry, binding attributes, cost effectiveness, and environmental benefits. The study examined the influence of the fly ash-based geopolymer stabilisation on the sedimentation and consolidation behaviours, mineralogy and microstructure of the fly ash-based geopolymer stabilised dredged mud.

Settling column tests were conducted to investigate the sedimentation behaviour of untreated and fly ash-based geopolymer stabilised dredged mud slurries. Standard one-dimensional consolidation (Oedometer) tests were used to evaluate the compressibility and consolidation characteristics of the untreated and the fly ash-based geopolymer stabilised dredged mud sediments. X-ray diffractometer (XRD) and scanning electron microscopy (SEM) with energy dispersive spectrometer (EDS) techniques were deployed to analyse the mineralogy and microstructure of the untreated and the fly ash-based geopolymer stabilised dredged mud.

The study found it is feasible to stabilise high water content dredged mud slurry with fly ash-based geopolymer binder. Fly ash-based geopolymer gel coating dredged mud particles in the slurry was found to be the main stabilisation mechanism. It is noted the geopolymer gel coating dredged mud particles in the slurry has exacerbated flocculation of the stabilised dredged mud slurry, extended its flocculation duration, reduced settling time and shorten overall sedimentation duration. The SEM with EDS analysis showed the fly ash-based geopolymer stabilisation has altered the microstructure of stabilised dredged mud, changed its particles arrangement and reduced its desiccation shrinkage cracks. Subsequently, the fly ash-based geopolymer stabilisation has improved the compressibility and consolidation properties of the stabilised dredged mud by reducing its coefficient of volume compressibility (m_v) and increasing its coefficient of consolidation (c_v) and permeability coefficient (k). However, the XRD analysis found no correlation between the fly ash-based geopolymer stabilisation and the mineralogy of the fly ash-based geopolymer stabilised dredged mud.

List of Publications

Journals

Jaditager, M., and Sivakugan, N. (2018) "Consolidation behaviour of fly ash-based geopolymer stabilised dredged mud" Journal of Waterway, Port, Coastal, and Ocean Engineering ASCE, 144(4), pp. 1 - 7.

Jaditager, M., and Sivakugan, N. (2017) "Influence of fly ash-based geopolymer binder on the sedimentation behaviour of dredged mud" Journal of Waterway, Port, Coastal, and Ocean Engineering ASCE, 143 (5). pp. 1- 9.

Jaditager, M., Lovisa, J., and Sivakugan, N. (2014) "Maintenance dredging at Port of Townsville" International Journal of Environmental, Chemical, Ecological and Geophysical Engineering, 8(12), pp. 734 -737.

Refereed Conference Proceedings

Jaditager, M., and Sivakugan, N. (2016) "Geotechnical site investigations for dredging works" Proceedings of the 5th International Conference on Geotechnical and Geophysical Site Characterisation, 2, pp.987- 990. From: 5th International Conference on Geotechnical and Geophysical Site Characterisation, 5th – 9th September 2016, Gold Coast QLD, Australia.

Jaditager, M., Lovisa, J., and Sivakugan, N. (2015a) "Capital dredging at the Port of Townsville" Proceedings of the Australasian Coasts and Ports Conference, pp. 120 -124. From: Australasian Coasts and Ports Conference, 15th - 18th September 2015, Auckland, New Zealand.

Jaditager, M., Lovisa, J., and Sivakugan, N. (2015b) "Settlement analysis of eastern reclamation area: the Port of Townsville" Proceedings of the 12th Australia New Zealand Conference on Geomechanics, pp. 1131-1135. From: ANZ 2015: 12th Australia New Zealand Conference on Geomechanics, 22nd - 25th February 2015, Wellington, New Zealand.

Table of Contents

List of figures

List of tables

List of notations

Notation	Definition	Units
CPT	Cone penetration test	[-]
CSD	Cutter suction dredge	[-]
DCP	Dynamic cone penetration test	[-]
$D(c)$	Total dissipation coefficient	[-]
DMT	Dilatometer test	[-]
C_c	Compression index	[-]
c_v	Coefficient of consolidation	[m²/year]
$C_\propto$	Secondary compression index	[-]
e_0	Initial void ratio	[-]
e	Void ratio	[-]
e_p	Void ratio at the end of primary consolidation	[-]
Δe	Change in soil void ratio due to consolidation settlement	[-]
EDS	Energy dispersive spectroscopy	[-]
G_s	Specific gravity	[-]
H_0	Initial soil specimen thickness	[m]
ΔH	Soil specimen thickness change due pressure increment	[m]
H_{dr}	Average longest drainage path during consolidation	[m]
k	Permeability coefficient	[m/s]
ISSMGE	International society for soil mechanics and geotechnical engineering	[-]
LAT	Lowest astronomical tide	[m]
LL	Liquid limit	[%]
m_v	Coefficient of volume compressibility	[kPa^{-1}]
m	Positive integer that has values range between 0 to ∞	[-]
NaOH	Sodium hydroxide	[-]
PI	Plasticity index	[%]
PL	Plastic limit	[%]

PIANC	Permanent international association of navigation congresses	[-]
pH	Power of Hydrogen	[-]
SEM	scanning electron microscopy	[-]
	Effective stress	[kPa]
$\Delta\sigma$	Effective stress increase that causes volumetric strain	[kPa]
$\Delta\sigma$	Pressure increase due to incremental loading	[kPa]
σ_c	Maximum past pressure	[kPa]
RL	Reduced level	[m]
RQD	Rock quality designation	[%]
SPT	Standard penetration test	[-]
s	Flux	[number of particles/m²/s]
S_c	Primary consolidation settlement	[mm]
S_i	Immediate (elastic) settlement	[mm]
S_T	Total settlement	[mm]
S_{sc}	Secondary consolidation settlement	[mm]
s_u	Undrained shear strength	[kN/m²]
TSHD	Trailing suction hopper dredge	[-]
t	Time	[s]
t_{90}	Time required to achieve 90% of soft soil specimen primary consolidation	[month]
T_v	Dimensionless time factor	[-]
ρ	Concentration	[number of particles/m³]
v	Particle velocity	[m/s]
v_s	Settling velocity of the solid phase	[m/s]
η	Concentration	[kg/m³]
n	Porosity	[-]
u_0	Initial pore water pressure	[kPa]
u	Pore water pressure	[kPa]
u_z	Excess pore pressure at time (t)	[kPa]

U	Average degree of consolidation for entire depth of soft soil layer at any time (t)	[%]
UCS	Unconfined compressive strength	[KN/m²]
γ_s	Unit weight of solid	[KN/m³]
γ_f	Unit weight of fluid	[KN/m³]
γ_w	Unit weight of water	[KN/m³]
W_{sk}	Total velocity function including permeability effects	[m/s]
XRD	X-ray diffractometer	[-]
x	Height of the accumulated particles layer	[m]
z	Depth	[m]

Chapter1: Introduction

1.1 General background

World population growth, economic development and subsequent urbanisation have resulted in demand for new land. There are several land reclamation projects that were undertaken across the world during last few decades to meet the demand for the new land (Van't Hoff and van der Kolff 2012). Land reclamation projects such as Palm Island in Dubai – United Arab Emirates, Maasvlakte Two land reclamation in Rotterdam, the Netherlands, Sydney airport in Australia, and Hong Kong airport to name few.

The technological advancement in hydraulic and civil engineering has made it possible to create a new land at reasonable cost, making Mark Tawin's old adage of "buy land they are not making any more" irrelevant. However, land reclamation using fill material that have favourable geotechnical properties such as sand and rock is expensive. On the other hand, the land that is reclaimed with cheaper fill material such as soft dredged mud comes with geotechnical challenges of low bearing capacity, high compressibility and slow self-weight consolidation.

Considerable portion of the global land reclamation projects are undertaken by ports. Ports beneficially use their dredged material for land reclamation as an environmentally acceptable alternative, and to meet the need for new land at the same time. In order to maintain the required safe draft for vessels, ports and waterways conduct regular maintenance dredging campaigns to remove sediments that accumulate in the navigation channels by natural processes (Jaditager et al. 2014). The capital dredging campaigns are undertaken to deepen and widen channels to cater for the ever-increasing ship sizes and the associated deeper draft requirements (Jaditager et al. 2015a).

For instance, capital and maintenance dredged material that is derived from the Port of Townsville – North Queensland Australia, is classified as high plasticity soft dredged mud that has geotechnical characteristics of high compressibility and slow consolidation. Therefore, the land reclaimed with soft dredged mud slurry such as the Port of Townsville's requires to be improved by reducing its excessive deformation and expediting its slow self-weight consolidation process. By self-weight consolidation only, the Port of Townsville's reclaimed land would take up to twenty-five years to be suitable to support port infrastructure foundations (Jaditager et al. 2015a).

To accelerate the slow self-weight consolidation process that would shorten the waiting time for reclaimed land to be ready to meet development timelines and to improve the stiffness of the land reclamation fill material, ports apply various dredged material stabilisation techniques. Surcharging, stone columns and lime stabilisation are among the ground improvement methods that were used by the Port of Townsville. These applied soft dredged material stabilisation methods suit the Port of Townsville's reclaimed land site conditions. These applied soft dredged stabilisation methods have resulted in different stabilised ground performance at different costs.

This experimental study has investigated the feasibility of stabilising the Port of Townsville dredged mud while it is still in slurry form using fly ash-based geopolymer binder. The fly ash-based geopolymer binder is chosen for the fact that it is not sensitive to the high-water content nature of the dredged mud slurry, cost effectiveness and its environmental benefits. Stabilisation of the dredged mud while it is still in its slurry form simulates land reclamation project sites where high-water content dredged mud is pumped into containment ponds and let to settle and self-weight consolidate to form land reclamation fill material. The stabilisation of the soft dredged mud while it is still in slurry form provides an opportunity to manipulate the geotechnical properties of the dredged mud sediment that is to be formed by slurry sedimentation and self-weight consolidation.

In dredging and land reclamation projects, understanding the geotechnical properties of the dredged material and the underlying natural subsurface is paramount. When considering the use of dredged mud as fill material for land reclamation works, the understanding of the time-dependent sedimentation and consolidation behaviour of the dredged mud slurry assist in informed selection of the appropriate dredging and reclamation techniques (Barros and Pinto 2008). The sedimentation behaviour of the dredged mud slurry defines land reclamation project parameters such as bund wall design; dredged material containment ponds network sequencing, weir box locations, and dredged mud slurry flow paths. Where, the consolidation behaviour of the soft dredged mud sediment is imperative in designing dredged material containment ponds capacity, predication of the soft dredged material consolidation rate and deformation amount that are critical for the design, construction and maintenance of infrastructure foundations.

1.2 Problem definition

Ports and waterways conduct capital and maintenance dredging campaigns in order to keep up with the ever-increasing ship sizes and to maintain the existing navigational channel, therefore, improving the navigational safety and operational efficiency of vessels movements. Most of the soft dredged mud slurry that is derived from these dredging campaigns is used as a structural fill material for land reclamation purposes to address land scarcity and environmental constraints around the dredged material placement alternatives.

On dredging and land reclamation with soft dredged mud slurry project site, dredge cutter heads and drag heads disintegrate the marine sediment and turn it into dispersed mud particles. The dredged mud particles suspend in water column and become waterborne, resulting in high water content dredged mud slurry. Then, the high-water content dredged mud slurry is pumped into land reclamation containment ponds to settle, self-weight consolidates to form soft land reclamation fill material.

Excessive foundation settlement and lengthy self-weight consolidation duration are typical problems face geotechnical engineers while dealing with land reclaimed by soft dredged mud. Soft dredged material stabilisation measures are usually undertaken to expedite the self-weight consolidation process and to improve the fill material compressibility to minimise the reclaimed ground settlement due to load transferred from constructed structures or traffic.

For the naturally formed soft soils, geotechnical engineers have no control on its formation processes. However, on a land reclamation with soft dredged mud slurry project site, there are several hours from the moment of placing the dredged mud slurry into containment ponds to the commencement of formation of the land reclamation fill material by sedimentation and self-weight consolidation. This time window is sufficient for an early geotechnical intervention to stabilise the high-water content dredged mud while it is still in its slurry stage, using dredged stabilisation binder. The proposed early geotechnical intervention is to stabilise the dredged mud slurry prior to the formation of the soft dredged mud sediment as land reclamation fill. Post its soil skeleton formation by sedimentation and self-weight consolidation, the soft dredged mud sediment will gain most of its undesired geotechnical properties.

Stabilisation of the soft dredged mud while it is still at slurry stage provides a chance to manipulate the sedimentation behaviour of the dredged mud slurry that controls the formation and microstructure of the resulting land reclamation fill material. The formation of cohesive soil sediment is a combination of settling and consolidation processes that influence the structure and the geotechnical properties of the formed sediment (Trofs et al. 1996). According to Low et al. (2008), the formation and the microstructure of marine clay are closely linked to its compressibility and consolidation properties.

Chemical admixtures such as cement, lime, and industrial by-products, electrokinetic consolidation, stone column, prefabricated vertical drains (PVDs), and surcharging are among the methods that are currently applied to improve the unfavoured geotechnical properties of the soft dredged material. In order to be effective, stone columns, prefabricated vertical drains and surcharging dredged material stabilisation techniques require self-weight consolidation of the fill material to gain sufficient stiffness to be traversed by the soil stabilisation plant and work force. This is a tedious and time-consuming exercise. For the chemical additives and electrokinetic methods to be effective, the land reclamation fill material that is to be stabilised requires dewatering to achieve water content below 250% (Malekzadeh 2016). Otherwise, the high water content compromises the concentration of the stabilising chemical admixtures and diminishes the electrokinetic induced physiochemical changes to the stabilised dredged material.

1.3 Objectives of the research study

The main objective of this research study is to explore the feasibility of stabilising 400% water content soft dredged mud slurry that is derived from the Port of Townsville using the fly ash-based geopolymer binder. The fly ash-based geopolymer material is extensively used in the concrete industry as an alternative replacement for Portland cement for its strength and binding attributes. This research study aimed at stabilising the dredged mud while it is still in slurry form. Stabilisation of dredged mud slurry provides an opportunity to control the sedimentation behaviour of the stabilised soft dredged mud which in turn controls the microstructure, compressibility and consolidation characteristic of the stabilised dredged mud sediment.

To ascertain the main objective of the research study, the following sub-objectives are also investigated:

- The sedimentation behaviour of the fly ash-based geopolymer stabilised dredged mud slurry.
- The mineralogy and microstructure of the fly ash-based geopolymer stabilised dredged mud.
- The compressibility and consolidation properties of fly ash-based geopolymer stabilised dredged mud.
- The consolidation rate and settlement amount of untreated and geopolymer stabilised dredged mud sediments.
- Environmental impacts of stabilising dredged mud slurry with fly ash-based geopolymer binder.
- Practical implications of the study findings on land reclamation with soft dredged mud slurry projects.
- On site application of the fly ash-based geopolymer stabilisation of dredged mud slurry on land reclamation with dredged mud slurry project site.

1.4 Scope of the research study

The scope of this research study project combines filed observations and laboratory testing components. The filed observations part comprised inspection of dredging operations and dredged mud slurry placement into dredged material containment ponds at the eastern reclamation area – the Port of Townsville. The filed observations also included monitoring of dredged mud slurry flow paths, settling patterns; land reclamation fill material dewatering, solar drying, and desiccation shrinkage cracks development on the land reclamation fill material and reclaimed ground improvement by surcharging.

The laboratory testing component of the research study included the followings:

- Preparation of dredged mud sample and fly ash-based geopolymer material;
- Determination of alkali activator liquid and fly ash-based geopolymer material mix designs;
- Remoulding and reconstituting of the Port of Townsville dredged material;
- Investigation of physical and index properties the Port of Townsville dredged mud;
- Selection of fly ash-based geopolymer dredged mud slurry stabilisation percentages;
- Stabilisation of the dredged mud slurry with the fly ash-based geopolymer binder at 6%, 12% and 18% by weight; and
- Conducting settling column, standard one-dimensional consolidation (Oedometer), and mineralogy and macrostructure tests.

X-ray diffractometer (XRD) was used to examine the potential of mineralogical changes in the stabilised dredged mud sediment due to the fly ash geopolymer binder stabilisation. Where scanning electron microscopy (SEM) with energy dispersive spectrometer (EDS) analysis is used to investigate the microstructural characteristics of the dried untreated and the fly ash-based geopolymer stabilised dredged mud specimens. The research project laboratory testing plan is outlined in Table 1.1 below.

Table 1.1 – Research project laboratory testing plan

Test category	Test name	Soil property/behaviour investigated	Australian standard designation
Sedimentation	Settling Column Test	Sedimentation Behaviour	
Index Properties	Atterberg Limits	Liquid Limit (LL)	1289.3.1.1
		Plastic Limit (PL)	129.3.2.1
		Plasticity Index (PI)	1289.3.3.1
	Specific Gravity	Specific Gravity (G_s)	1289.3.5.1
	Particle Size Distribution by Sieving in Combination with Hydrometer Test	Particle Size Distribution Curve	1289.3.6.2
Consolidation	Standard One-Dimensional Consolidation Test	Coefficient of Volume Compressibility (m_v) Void Ratio (e) Coefficient of Consolidation (c_v) Permeability Coefficient (k)	1289.6.6.1
Mineralogy	X-Ray Diffraction (XRD)	Mineral Phase Concentration	
Morphology	Scanning Electron Microscopy (SEM) with Energy Dispersive Spectroscopy (EDS)	Microstructure	

1.5 Relevance of the research study

Land reclamation is increasingly becoming necessary for industrial and residential purposes. Technological advances in civil engineering, has led land reclamation to become an attractive solution for the land scarcity problem that faces densely populated countries such as China and Bangladesh, as well as not so populous countries like Australia and United Arab Emirates. Dredging and land reclamation literature showed, by year 2008 China has reclaimed over 13, 400 square kilometres of land, and China’s demand for more reclaimed land is estimated to reach further 5,800 square kilometres by year 2020 (Naylor and Cao 2016).

According to Jaditager et al. (2015b) successive maintenance and capital dredging campaigns ports and waterways conduct around the world result in millions of cubic metres of dredged mud slurry pumped and deposited into land reclamation ponds thereby forming new land (Figure 1.1).

Figure 1.1- Dredging and dredged material placement operation at Port of Townsville – June 2017

The generated dredged mud slurry goes through sedimentation and self-weight consolidation when pumped into settling pond to form land reclamation fill material. For instance, The Port of Townsville has deposited over two million cubic meters of soft dredged mud into its eastern reclamation area creating over 100 hectares of reclaimed land during the last three decades, and plans to reclaim another 110 hectares of land over the next thirty years (Jaditager et al 2016). The Port of Townsville's land reclamation works progression over the period between 1991 and 2018 is shown on Figure 1.2 below.

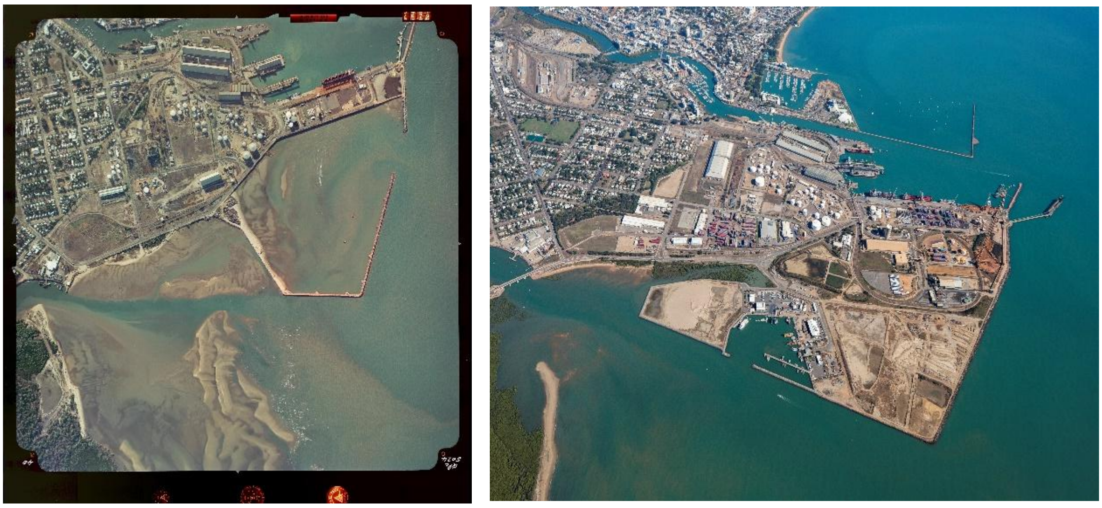


Figure 1.2 – Aerial photo of the Port of Townsville that are taken in 1991 and 2018 respectively

For a land reclamation project, where high water content soft dredged mud slurry is used, the dredged mud particles hydraulic retention time, settling pattern and over-all sedimentation duration guide dredged material containment ponds network design and sequencing, and tail water management plans. On the other hand, the consolidation rate and settlement amount of the dredged mud sediment are vital geotechnical design inputs for reclaimed ground improvement method and foundation type selections. According to Merckelbach and Karanenburg (2004), predication of the consolidation behaviour of soft soils is instrumental in the geotechnical engineering practice.

The land that is reclaimed using soft dredged material requires to be improved to reduce its compressibility and expedite its slow self-weight consolidation process to be suitable to support the infrastructure foundations. In this research study, the feasibility of stabilising high-water content soft dredged mud slurry with fly ash-based geopolymer binder is investigated in laboratory. Exploring the potential of treating the soft dredged mud slurry with fly ash-based geopolymer binder and the influence of the fly ash-based geopolymer stabilisation on sedimentation and consolidation behaviour of the geopolymer stabilised dredged mud have the following significances:

- This research study will contribute to the effort of finding alternative soft dredged material stabilisation techniques by proposing the fly ash-based geopolymer binder as environmentally friendly and cost-effective binder for dredged mud slurry stabilisation.
- The study encourages the direction of stabilising the dredged mud while it is still in slurry form, prior to the formation of the land reclamation fill material by sedimentation and self-weight consolidation. In other words, this study introduces an early geotechnical intervention approach to manipulate the sedimentation behaviour of the soft dredged mud slurry that is closely linked to compressibility and consolidation characteristic of the resulting land reclamation fill material.
- The sedimentation behaviour of fly ash-based geopolymer stabilised dredged mud slurry guides dredged material containment ponds holding capacity, pond network sequencing and dredged material flow paths configuration.

- The compressibility and consolidation characteristics of stabilised dredged mud sediment are salient input parameters for modelling and prediction of consolidation duration and settlement (deformation) amount of reclaimed fill material.
- As by-product of coal fired power generation, Australia produces around 13 million tonnes of fly ash every year (Cement Australia 2011). One third of Australia's annual production of fly ash is used in concrete, construction, mining and other industries. The remaining 8.6 million tonnes are disposed into landfill and ash storage lagoons as waste material (Heeley, 2003). Beneficial use of any amount of the waste fly ash for geopolymer material synthesisation for dredged mud stabilisation purposes will reduce waste; contribute to saving cost of disposing and managing the fly ash and improve environment.
- Although it was discovered in the late 1970's, geopolymer technology and its applications are still at the research stage (Hardjito, 2005 and Davidovits 2015). Usage of the fly ash-based geopolymer binder as soft soil stabiliser will add to the existing geopolymer application research and will contribute to the civil/geotechnical engineering knowledge.
- The findings of this experimental study encourage geotechnical researchers and practicing engineers to try new soft soil stabilisation materials and methods.

1.6 Thesis organization

This dissertation comprises eight chapters. Chapter 1 of the dissertation outlines a general background about dredging land reclamation with soft dredged material and identify the geotechnical challenges that come with land reclaimed with soft dredged material. Chapters 1 also defines the research problem, gives research study scope and objectives, relevance of the research study to the geotechnical design of land reclamation projects, and brief overview of the thesis organisation.

Chapter 2overviews the historical development of Kynch's theory of sedimentation and its relevance to the settling of soft soil slurries, the assumptions upon which Kynch's sedimentation theory was based and parameters that govern the soft soil sedimentation process.

Application of the Kynch's sedimentation theory on geotechnical engineering processes of soft soil slurry settling pattern and soft soil sediment formation that occur on land reclamation sites are also discussed in Chapter 2. Terazghi's theory of consolidation, assumptions and boundary conditions that are required when describing the rate of one dimensional consolidation of saturated clay soils are studied in Chapter 2. General overview on consolidation of soft soil sediments, geotechnical investigations for dredging and land reclamation works, and a brief review of dredging and reclamation operations at the Port of Townsville are also discussed within Chapter 2 of the dissertation. In addition, an overview of the current practices of soft dredged material stabilisation techniques such as chemical admixtures, electrokinetic, stone columns, prefabricated vertical drains and surcharging, and the limitations of these techniques are given in Chapter 2 .

Chapter 3 describes the experimental study of soft dredged mud stabilisation with the fly ash-based geopolymer. Material used (dredged mud, fly ash and alkali activator liquid), experimental set up, stabilisation percentages, geopolymer binder synthesisation, and dredged mud slurry stabilisation with the fly ash-based geopolymer binder and its environmental impacts are also explained within Chapter 3. The results of dredged mud slurry stabilisation with fly ash-based geopolymer and onsite dredged mud slurry stabilisation with the fly ash-based geopolymer binder concept design are also discussed in Chapter 3.

Chapter 4 of the dissertation details laboratory experimental study of the sedimentation behaviour of the Port of Townsville's dredged mud slurries that are untreated and fly ash-based geopolymer stabilised at 6 %, 12% and 18% by weight. The untreated and the fly ash-based geopolymer stabilised dredged mud slurries sedimentation characteristics are outlined in this chapter. The dredged mud sediment water mixture interface heights movements with elapsed time, dredged particles hydraulic retention time, settling patterns, flocculation stage duration and over all sedimentation time are investigated in detail within chapter 4. Chapter 4 also shows the final sediments column heights of the resulting untreated and the fly ash-based geopolymer stabilised dredged mud sediment.

Chapter 5 outlines the influence of the fly ash-based geopolymer stabilisation on the mineralogy and microstructure of the geopolymer stabilised dredged mud sediments. The dredged mud sediment specimen's preparation, x-ray diffractions analysis of the untreated and the fly ash-based geopolymer stabilised dredged mud sediments and the corresponding mineral phase concentrations are analyzed in Chapter 5. The influence of the fly ash-based geopolymer stabilisation on the mineralogy of the stabilised dredged mud sediment, SEM with EDS elemental analysis, macro characterisation and SEM micrographs of untreated and geopolymer stabilised dredged mud are also investigated in Chapter 5.

Chapter 6 of the dissertation deals with laboratory examination of the consolidation behaviour of the untreated and the fly ash-based geopolymer stabilised dredged mud sediments by studying their volume compressibility and consolidation characteristics. Preparation of the untreated and the fly ash-based geopolymer stabilised dredged mud specimens for Oedometer testing, Oedometer test program, the dredged mud specimen's incremental loading, specimen's deformation versus time data logging and consolidation curves fitting method are detailed in Chapter 6. Geotechnical properties of coefficient of volume compressibility (m_v), void ratio (e), coefficient of consolidation (c_v) and permeability coefficient (k) of the untreated and geopolymer stabilised dredged mud are also studied in Chapter 6.

Chapter 7 of the dissertation is a case study of settlement analysis of the eastern reclamation area at the Port of Townsville. The Port of Townsville's eastern reclamation area site description, geological settings and geotechnical site investigations that are required for reclaimed ground settlement predictions are detailed in Chapter 7. Reclaimed ground settlement analysis method, along with geotechnical design input parameters; reclaimed ground consolidation rate and settlement amount estimates are presented and discussed in Chapter 7. Finally, Chapter 8 of the dissertation incorporates a summary of the research study findings, conclusion, and recommendations for future studies.

Chapter 2: Literature Review

2.1 Theoretical background

2.1.1 Sedimentation theory

There are two major theories that are governing soft soil sedimentation and consolidation behaviours, namely, Kynch's (1952) theory for sedimentation and Terazghi's (1923) theory for consolidation. Historically, sedimentation and consolidation theories emerged independently (Toorman 1996). To describe sedimentation of solid particle through fluid column under gravity as a wave propagation phenomenon, Kynch built his sedimentation theory based on the following assumptions:

- At any point in dispersion, the velocity of fall of a particle depends only on the local concentration of the particles in the neighbourhood (equation 2.1).

$$s = \rho v \qquad (2.1)$$

Where, s is flux (number of particles crossing a horizontal section per unit area per unit time), ρ is concentration (number of particle per unit volume), and v is particle settling velocity.

- The settling process is determined from continuity equation without knowing details of forces on the particles (equation 2.2).

$$\frac{\partial \rho}{\partial t} = \frac{\partial s}{\partial z} \qquad (2.2)$$

Where, t represents time and z is height of the accumulated particles layer.

According to Lin (1983) dredged material settles in flocs, but not as individual particles. Thus Kynch's theory of sedimentation is not applicable. Camenen and van Bang (2011) used Toorman (1996) sedimentation and self-weight consolidation – general unifying theory, which considers geotechnical engineering processes of soft soil particles settling and soft soil sediment formation to compose unified general one-dimensional equation (2.3).

$$\frac{\partial c}{\partial t} + \frac{\partial}{\partial z}[W_{sk}\,(c)c] + \frac{\partial}{\partial z}\left[D(c)\frac{\partial c}{\partial z}\right] = 0 \qquad (2.3)$$

W_{sk} is the total settling velocity function including permeability effects, $D(c)$ is the total dissipation coefficient, z is vertical coordinate, c is the volumetric concentration matter, and t is time.

With his unified general one-dimensional equation, Toorman attempted to describe the sedimentation and self-weight consolidation of soft soil – water mixture into one time-dependent differential equation similar to the illustration that was proposed by Krizek (2004) in Figure 2.1 below.

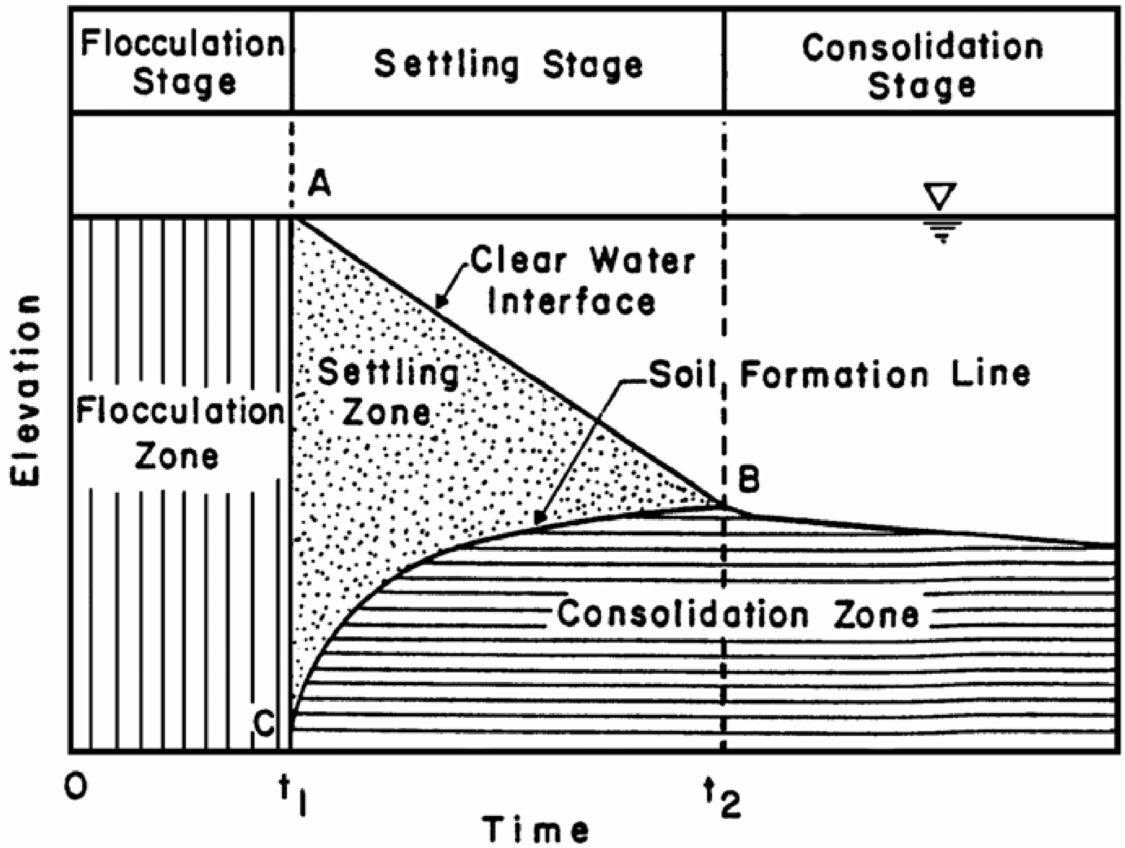


Figure 2.1 – Illustration of time- dependent, flocculation, sedimentation and consolidation of clay slurry modified Imai, 1981 (Krizek 2004)

On the Figure (2.1), point A denotes the height of slurry (soft soil – water mixture) in the settling tube, where point B denotes the height of the sediment column, and point C is the start of the soft soil formation line. t_1 is the time at which settling stage starts, and t_2 is the time required to complete the sedimentation of the soft soil. Line AB is clear water – soil mixture interface height change with the elapsed time. Line CB is the soft soil sediment formation curve during the slurry sedimentation stage.

According to Camenen et al (2011), Toorman (1996) general unifying theory of sedimentation and self-weight consolidation describes a sedimentation/ consolidation process in three main regimes:

1- Hindered regime, where the settling velocity is mainly driven by the concentration of the particles (effective stress $\sigma = 0$). This regime 1 corresponds to sedimentation.
2- Permeability regime, where the settling velocity function is mainly driven by the permeability, this mode physically represents compression and expulsion of pore water ($\sigma \approx 0$).
3- Effective stress regime, where sediment deformation causes further compression ($\sigma > 0$). Regimes 2 and 3 correspond to consolidation.

2.1.1.1 Sedimentation of soft soil slurries

Soil sediments are a product of soil erosion, whereby soil disaggregates into its particles, and then the particles carried away by wind, water or ice into a water to settle out at the bottom of the water column to form a soft soil layer (Maher et al. 2013). According to Khan (2017), soft soil slurries are soil with no transferable effective stress; as such soil particle to particle contact is not established to allow transfer of stresses. In the soft soil literature, settling is defined as falling of suspended soil particles through a liquid column of soft soil sediment out of slurry. Where sedimentation is the process by which the settling particles situated at the bottom of the liquid column. Most of the geotechnical researches are concerned about the behaviour of soft soils post its formation. However, soft soil literature shows pre-sedimentation behaviour of soft soil slurries is still of great interest for civil and mining engineering industries such as dredging and land reclamation, and mine tails (Krizek 2004).

Sedimentation and suspension flow of soft soil particles play an important role in geotechnical engineering application of land reclamation with soft dredging mud slurries. In land reclamation projects, the soft dredged mud slurry is hydraulically placed into containment ponds to undergo sedimentation and self-weight consolidation to form land reclamation fill material. Depending on the depositional environment, soil formed during sedimentation process may be in segregated or homogenous structure (McRobert and Nixon 1976). Understanding of settling patterns of soft soil slurries, sedimentation and subsequent formation of soft soil skeleton were interest of many geotechnical researchers. Since Kynch's theory of sedimentation in early 1950s, there have been numerous studies on sedimentation behaviour of soft soils. McRoberts and Nixon (1976); Imai et al. (1979); Imai (1980), Imai (1981); Been and Sills (1981); Concha and Bustos (1987); Tan et al. (1990); Brown and Heywood (1991); Sridharan and Parkash (1999); and Azam (2011) are some examples.

According to Imai (1979), the settling behaviour of a soft soil-water mixture is governed by sophisticated interactions of physicochemical factors like soil mineral type, dissolved electrolytes, concentration of solid materials and salt concentration in water. In general, soft soil particles tend to flocculate when the salt concentration of water in soil-water mixture is considerably high. van Paassen and Gareau (2004) have advised compressibility characteristics of soft soil sediments are function of effective its stress level, water content, and water salinity. For high water content soft soil water mixtures such as land reclamation dredged mud slurry, there are various factors that define the structure of the final soft sediment to be formed by slurry sedimentation and self-weight consolidation processes.

Sridharan and Parkash (1999) have advised, the main forces that exist in fine grained soil-water system are: forces due to self-weigh (constant force), and electrical forces (distance forces) which dominate the behaviour of the fine grained soil water system. Di Maio et al. (2002) have proposed that in a high water content soft soil water mixture, the effect of mechanical forces such as inter-particle friction is less significant. In such soft soil water mixture, soil particles may settle as discrete particles or as flocs in the water column, with settling progresses on the top, the bottom layer consolidates due to the self-weight of soil mass lying above (Been and Sills 1981). Based on precise observation on clay settling phenomena, Imai (1980) classified settling behaviour of dilute clay water mixtures into four stages: dispersed free settling, flocculated free settling, zone settling and consolidation settling. According to Imai's observations, degree of flocculation and degree of particle interaction are the two main factors that are causing difference in soft soil particles settling type.

Weggel (1983) has described Kynch's (1952) theory of sedimentation as a kinematic model that uses a continuity equation as well as the simple assumption of the velocity of settling particle as a function of local concentration only. Kynch's theory sedimentation is considered to be incapable of describing settling behaviour of slurries such as dredged mud and does not account for effective stress (Alexis et al. 1992). To extend the theory to clayey slurries, Concha and Bustos (1987) have modified Kynch's theory by taking soft soil slurry compressibility into consideration, which enabled simulation of slurry sedimentation process such as that occurs at land reclamation with dredged mud slurry projects sites. Kynch's modified theory of sedimentation remains practical and soil permeability is the only property required to be determined. According to Tan et al. (1990), soft soil permeability can be obtained from its clear water – sediment interface height movement with time curve.

Azam (2011) has obtained the permeability of polymer amended laterite slurries using the slope of the initial straight-line part of the interface height versus time curve on a linear scale. Whereas, McRobert and Morgenstern (1974) have employed settling tube experiment to study thaw consolidation by determining permeability of silt at high void ratio. A dilute suspension of soil particles in water will normally flocculate and settle under gravity to form a bed of consolidating soil (Been 1980). McRobert and Nixon (1976) used an experimental method to determine at what concentration or water content the dispersion becomes a soil in geotechnical sense (i.e. at what point effective stress starts to exist).

Tan et al. (1990) have investigated Kynch's assumption of the settling velocity of soil particle as a function of concentration alone. Tan et al. (1990) found the settling velocity depends on the flocculation effect as well. The modified Kynch's theory of sedimentation has showed slurry permeability versus void ratio relationship can be determined from its clear water – sediment interface height movement versus time curve. When using clayey suspensions such as dredged mud slurry as fill material for land reclamation works, the suspended solid in the sea water settles under its self-weigh until an equilibrium state has arrived. The soft soil slurry settling pattern is dependent on size and shape of particles, concentration of the particles, and soil mineralogy. Due to interaction of these factors, the soil particles may undergo particulate settling or hindered settling where the particles move en masse (Brown and Heywood1991). To account for the other factors that influence the soft soil settling process beside slurry concentration, McRobert and Nixon (1976) extended Kynch's theory of sedimentation by defining concentration (η) as the mass of particles per unit volume while considering the velocity at a point rather than of a particle.

Concentration (η) is a function of flux (s) , concentration (ρ) and porosity(n) which is given by equation (2.4):

$$\eta = (1 - n)\rho s \tag{2.4}$$

By defining flux (s) as a function of the settling velocity of the solid phase (v_s) and mass of particles per unit volume (η); Kynch's principal assumption; equation (2.1) can be rewritten as (equation 2.5):

$$v_s = v_s(\eta) \tag{2.5}$$

Tan et al. (1990), employed concentration (η) and settling velocity (v_s) relationship in dispersion governing continuity equations, equilibrium and Darcy's law to deduce (equation 2.6):

$$v_s = k\frac{\eta}{\rho s}\left(\frac{\gamma_s}{\gamma_f} - 1\right)\left[1 + \frac{\rho s}{\eta(\gamma_s - \gamma_f)}\frac{\partial \sigma}{\partial x}\right] \tag{2.6}$$

Where, k is soil permeability, σ is effective stress, x is height of the accumulated particles layer; γ_s and γ_f are unit weights of solid and fluid, respectively.

It is generally accepted that during the sedimentation stage, there is no effective stress and the slurry behaves like a fluid (Imai1981). Once soil structure (sediment) formed at the bottom of the soil column, the effective stress can be measured, the slurry becomes a soil and consolidation theory is applicable (Imai1981; Been 1980). During the settling stage, the effective stress (σ) is equal to zero, no strain occurs on the upper settling zone and the permeability is function of concentration, accordingly, equation (2.6) can be re-written as (equation 2.7):

$$v_s = k\frac{\eta}{\rho s}\left(\frac{\gamma_s}{\gamma_f} - 1\right) \tag{2.7}$$

Using equation (2.7), Tan et al. (1990) obtained permeability (k) versus concentration (η) relationship from settling velocity (v_s) versus concentration (η) relationship that is determined from the surface settlement versus time curve of settling clay slurry.

Equation (2.7) is the modified Kynch's theory of sedimentation which Tan et al. (1990) derived to describe the sedimentation of clay slurries. Substituting (η) from equation (2.4) into equation (2.7) yields equation 2.8:

$$v_s = k(1-n)\left(\frac{\gamma_s}{\gamma_f} - 1\right) \quad (2.8)$$

Using saturated soil weight–volume phase relationships that were described by Das and Sobhan (2012), unit weight γ_s relates to porosity (n) and specific gravity (G_s) as follows equation (2.9):

$$\gamma_s = G_s\gamma_f(1-n) \quad (2.9)$$

Combining equations (2.8) and (2.9) yields equation (2.10):

$$v_s = k\frac{\gamma_s}{\gamma_f G_s}\left(\frac{\gamma_s}{\gamma_f} - 1\right) \quad (2.10)$$

With equation (2.10), for a clayey flocculating dispersion, permeability of clay slurry can be determined from its weight- volume phase relationship and settling column test, as v_s is slope of clear water – soil interface height movement versus time curve. Pane and Schiffman (1997) have confirmed permeability of soft soil particles suspension can be estimated from settling velocity of the early stages of sedimentation test for a wide range of mixture porosity, extending from soil condition (n = 0.5) to suspension conditions (n = 0.99).

2.1.2 Consolidation theory

The consolidation theory describes the behaviour of soil-water mixture from the moment at which effective stress starts to exist. Sedimentation occurs whereby particles and flocs settle out from suspension, material build up, and the particles and the flocs are brought together. When the particles become sufficiently close to develop a structure, the resulting physical behaviour can be described by self-weight consolidation process (Blewett et al. 2001). According to Lovisa (2012) Terazghi's consolidation theory is an elegant theory that provided the basis for developing the principle of effective stress and led to the understanding of strength and compressibility characteristic of soft soils.

Terzaghi (1925), proposed the consolidation theory to describe rate of one-dimensional consolidation for saturated clay soils that are subjected to vertical loading, based on the following six assumptions:

1- The clay-water system is homogenous.
2- Saturation is complete.
3- Compressibility of water is negligible.
4- Compressibility of soil grains is negligible; however, soil grains rearrange.
5- The flow of water is in one direction only. In the direction of compression.
6- Darcy’s law is valid.

A saturated clayey soil layer that has height of ($2H_{dr}$), sandwiched between two highly permeable sand layers and subjected to an increased pressure of ($\Delta\sigma$)(Figure 2.2), the pore water pressure at any point A in the soil layer will increase (Das and Sobhan 2012). For one-dimensional consolidation, water will be squeezed out in the direction of the compression.

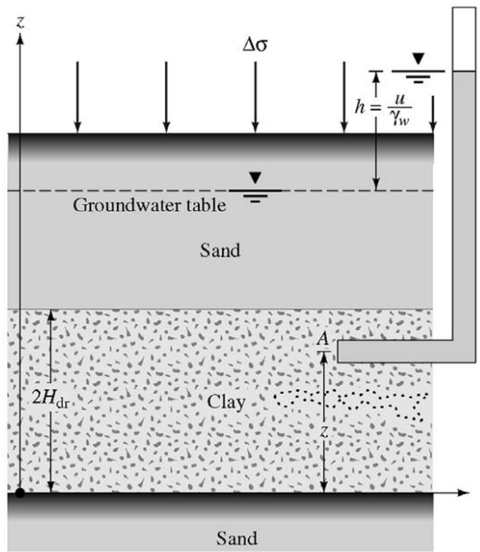


Figure 2.2 – Schematic of saturated clay layer undergoing consolidation (Das and Sobhan 2012)

With his six assumptions, Terzaghi (1925) has established the basic differential equation for the one-dimensional consolidation theory to describe the variation of pore water pressure (u) with time (t) and depth (z) through coefficient of consolidation (c_v) equation (2.11):

$$\frac{\partial u}{\partial t} = c_v \frac{\partial \text{ u}}{\partial \text{z}} \quad (2.11)$$

Taylor (1948) has solved Terzaghi's one-dimensional consolidation theory differential equation (2.11) for single and double drainage boundary conditions. The single drainage condition when the water flows out of the soil layer at the top or bottom, where, for the double drainage is in case of water flows at both top and bottom.

To determine the coefficient of consolidation of soft soil from its deformation versus elapsed time data, soft soil consolidation curve is needed to be plotted. There are several curve fitting procedures for plotting the soil specimens' settlement versus elapsed time graphs. However, Taylor (1942) square-root of time and Cassagrande and Fadum (1940) logarithm of time curve fitting methods are the most used. For instances, where Taylor (1942) square-root of time curve fitting is used, the coefficients of consolidation of the soft soil sediments that correspondence to each effective stress are estimated using below equation (2.12):

$$c_v = 0.848 \frac{H_{dr}^2}{t_{90}} \quad (2.12)$$

where (H_{dr}) is average longest drainage path during consolidation, and (t_{90}) is the time required to achieve 90% of the soft soil specimen primary consolidation.

Initial water content and saturated soft soil phase relations can be used to establish the initial void ratio of the soft soil specimens under investigation. According to Das and Sobhan (2012), the void ratio of a soil specimen is function of specimen's height of solids and height of voids. Thus, decrease in soft soil specimen void ratio (Δe) due consolidation settlement is given by equation (2.13):

$$\Delta e = \frac{\Delta H}{H_0} [1 + e_0 \ ] \quad (2.13)$$

(H_0) is initial soil specimen thickness,(ΔH) is soil specimen thickness change due vertical pressure increment and($\Delta\sigma$) is effective stress increase that causes the volumetric strain of the consolidating soft soil layer.

During the soft soil one-dimensional consolidation, the coefficient of volume compressibility (m_v) measures the extent of the volumetric strain a saturated soft soil layer would experience per unit vertical stress. Sivakugan and Das (2010) have proposed for one-dimensional consolidation, where only vertical strain exist (i.e. horizontal cross section of soil specimen remains unchanged), the coefficient of volume compressibility (m_v) is defined by equation (2.14):

$$m_v = \frac{(\Delta H/H_0)}{(\Delta\sigma')} = \frac{(\Delta e/(1+e_0))}{(\Delta\sigma')} \quad (2.14)$$

The primary consolidation of saturated soft clay soil layer occurs as result of soil's excess pore water pressure dissipation by water drainage out of the soft soil layer. Soil permeability (K) measures the easiness of water flow through the soil matrix; as such, soil permeability (K) is an important parameter for soil consolidation settlement analysis. Rajasekaran and Narasimha (2002) estimated the permeability of lime stabilised marine clay that was consolidating under a constant total pressure based on (m_v),(c_v) and unit weight of water (γ_w) equation (2.15):

$$k = m_v\, c_v\, \gamma_w \quad (2.15)$$

Expressing the soft soil layer excess pore water pressure as function of two variables (depth *z* and time *t*); Lovisa (2012) has solved Terazghi's basic differential equation (2.11) using Fourier series for the following boundary conditions:

z = 0, u = 0 (in case there is a complete drain at the base of the soil layer).

z = $2H_{dr}$, u = 0 (in case there is a complete drain at the top of the soil layer).

t = 0, $u = u_0$, (at the start of the consolidation, the initial excess pore water pressure is equal to excess pore pressure that is caused by the increased stress ($\Delta\sigma$).

Solving equation (2.11) for the above boundary conditions yields equation (2.16):

$$u = \sum_{m=0}^{m=} \frac{2u_0}{M} \sin\left(\frac{Mz}{H_{dr}}\right) e^{-M^2 T_v} \qquad (2.16)$$

Where, $M = \frac{\pi}{2}(2m+1)$, (m) is a positive integer that has values ranges from 0 to ∞, z is depth, (u_0) is initial excess pore water pressure, and (T_v) is a dimensionless time factor. (T_v) can be expressed as a function of (c_v), (t) and (H_{dr}) as shown in equation (2.17):

$$T_v = \frac{c_v.t}{H_dr^2} \qquad (2.17)$$

As long as the soft soil layer pore water pressure dissipation process is continuous, the soft soil layer consolidation will progress. The degree of consolidation (U_z) at a distance (z) at any time (t) is given by equation (2.18) (Das and Sobhan (2012):

$$U_z = \frac{u_0 - u_z}{u_0} = 1 - \frac{u_z}{u_0} \qquad (2.18)$$

Where, u_z is excess pore pressure at time (t).

The average degree of consolidation U for the entire depth of the clay layer at any time (t) is defined by equation (2.19):

$$U = \frac{S_c(t)}{S_c} = 1 - \frac{\frac{1}{2H_dr}\int_0^{2Hdr} uzdz}{u_0} \qquad (2.19)$$

$S_{c(t)}$ is settlement of the soft soil layer at time (t) and (S_c) is the ultimate settlement of the consolidating soil layer. By substituting u in equation (2.16) into equation (2.19) yields equation (2.20):

$$U = 1 - \sum_{m=0}^{m=} \frac{2}{M^2} e^{-M^2 T_v} \qquad (2.20)$$

Solving equation (2.20) for an average degree of consolidation U and time factor T_v for boundary conditions where u_0 remains the same for the entire depth of the consolidating layer will result to a relationship between average degree of consolidation (U), and time factor (T_v) . Thus, the average degree of consolidation percentage ($U\%$) versus time factor (T_v) curve can be constructed using standard one-dimensional consolidation test results.

2.1.2.1 Consolidation of soft soil sediments

All soils exhibit consolidation when subjected to stress and an increase in its pore water pressure. According to Lovisa (2012), granular soils such as sand that have relatively high permeability, consolidate instantaneously at the time of pressure application for the fact that their pore water pressure dissipation process is fast. In contrast, the consolidation of fine-grained soil such as clay is expected to take a prolonged period of time for their low permeability attribute. Raju et al. (1995) have described the consolidation of soft soil sediments as one of the most important behaviours of saturated soils that is needed to be understood to enable accurate prediction of the amount and the rate of settlement of these soft soils.

The consolidation of saturated soft soil sediment is a time dependent process whereby the dissipation of pore water pressure influences the geotechnical characteristics of the soft soil. Since inception of Terazghi's theory of consolidation in mid-1920's, substantial amount of research have been conducted to enhance better understanding of the consolidation behaviour of soft soils. Beens and Sills (1981), Cargill (1984), Kassim and Huey (2000), Feng et al. (2001), Morris (2003), Schlue et al. (2009), Lovisa (2012), Ganesalingam (2013), Haase and Shanz (2016) and Li et al. (2017) to name some.

The following general conclusions can be drawn from the reviewed soft soil consolidation literature:

- Standard one-dimensional consolidation (Oedometer) test is widely used in laboratory to investigate the consolidation behaviour of saturated soft soils.
- To account for soil geometrical nonlinearity and non-Darcian flow that is not covered by Terazghi's theory of consolidation, occasionally, numerical models such as finite difference method are used to describe the consolidation behaviour of soft soils.
- For the consolidation behaviour of the clays, soil parameters of coefficient of volume compressibility (m_v), coefficient of consolidation (c_v), permeability coefficient (k), compression index ($\mathrm{C_c}$) and secondary recompression index ($\mathrm{C}_{\propto}$) are widely investigated.

- Soft soil consolidation behaviour can also be investigated in terms of its excess pore water pressure dissipation, degree of consolidation, average degree of consolidation or percentage settlement.
- To plot soil specimen deformation versus time graphs for the determination of coefficient of consolidation (c_v); square-root-of time (Talyor 1942) and logarithm of time (Cassagrande and Fadum 1940) curve fitting procedures are often employed. In contrast, hyperbola (Sriharan and Prakash 1985) and early stage logarithm of time (Robinson and Allam 1996) curve fitting methods are less used.
- Research indicates laboratory obtained coefficient of consolidation (c_v) is more conservative compared to its field estimated value.
- There is a considerable debate among the geotechnical researchers and practitioners around the isotropy of the coefficient of consolidation of soft soil.

2.1.3 Geopolymer synthesisation mechanisms

Geopolymers are mineral of geological origin comprised chains or networks of mineral molecules that are linked with covalent bonds (Davidovits 2017). According to Davidovits (1991), geopolymer are used in various industries such as automobile, aerospace, no-ferrous, plastic and civil engineering. Motorwala (2015) has defined the geopolymerisation as a three steps process that is shown in Figure 2.3.

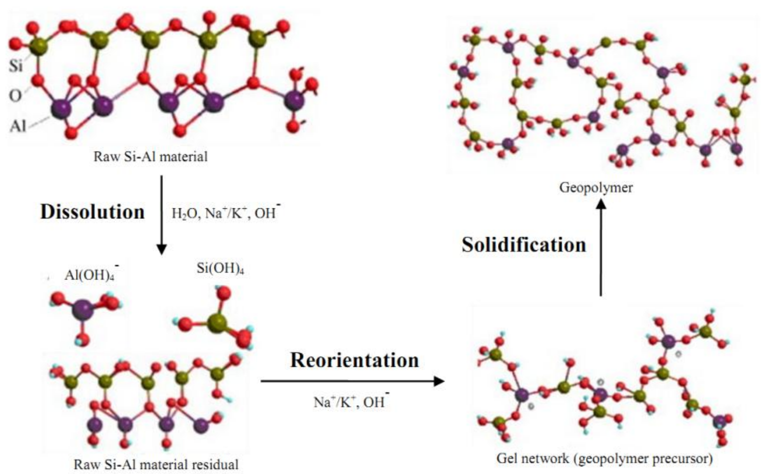


Figure 2.3 - Typical chemical reaction mechanisms of geopolymerisation process (He 2012)

The interrelated three steps overlap with each other and occur almost simultaneously as follows:

- Dissolution of silica-alumina (Si -Al) atoms from source material of geological origin through the action of hydroxide ions.
- Transportation, reorientation or condensation of precursor ions into molecules that are bonded to other identical molecules forming a polymer chain of (Si – O – Al – O) or (- Si – O – Al – O – Si – O –) known as monomers.
- Setting poly-condensation /polymerisation of monomers into polymeric structure.

2.1.3.1 Exothermic and geopolymeric chemical reactions

Davidovits (2008), the father of geopolymers, considers geopolymer as new materials suitable for coating and adhesives, binders for fibre composites, waste encapsulation and cement for concrete. The geopolymer binders can be produced by a polymeric reaction of alkaline liquids with alumina-silicate source materials of geological origin or by-product materials like fly ash and rice husk ash. Geopolymerisation process involves a fast-chemical reaction under alkaline condition on Si-Al minerals results in a three-dimensional polymeric chain and ring structure consisting of Si-O-Al-O bonds.

According to Abdullah et al. (2011), geopolymerisation chemical reaction can be described by the following general empirical formula:

$$Mn[-(SiO_2)\ z\text{-}(Al_2O_3)]\ n.WH_2O \qquad (2.21)$$

Where, M is alkaline element or cation (Na, K), the symbol (-) indicates presence of bond. Z is (SiO_2/ Al_2O_3) ratio of aluminosilicate source material; Z is an integer that is equal to: 1, 2, 3 or higher. Where, n is degree of polycondenstaion or polymerization that defined by Z. For instance, when Z is equal to 2, n is equal to 1 and the yielding geopolymer has monomeric units of poly-sialate-siloxo (-Si-O-Al-O- Si-O-) that was described by Cioffi et al. (2003). For Z equal to 3, the corresponding monmmeric are poly-sialate-diloxo (- Si-O-Al-O- Si-O- Si-O-). W is the number of water molecules.

The formation of geopolymer material is result of the following exothermic and geopolymeric chemical reactions:

Exothermic equation (releases heat):

$$n(Si_2O_5,\ Al_2O_2) + 2nSi_2O + 4nH_2O \xrightarrow{NaOH/KOH} (Na,K)^{+} + n(OH)_3\text{-}\ Si - O\ \text{-}\ \underset{|\atop (OH)_2}{Al^{-}}\ \text{–}Si\text{-}O\text{-}(OH)_3 \qquad (2.22)$$

(Si Al Materials) (Geopolymer precursor) (gel)

Geopolymeric equation:

$$n(OH)_3\ \text{-}\ Si\text{-}O\text{-}\underset{|\atop (OH)_2}{Al^{-}}\text{-}Si\text{-}O\text{-}(OH)_3 \xrightarrow{NaOH/KOH} (Na,K)^{+}\ \text{-}\ (\text{-}\underset{|\atop O}{Si}\text{-}O\text{-}\underset{|\atop O}{Al^{-}}\text{-}O\text{-}\underset{|\atop O}{Si}\text{-}O\text{-}) + 4nH_2O \qquad (2.23)$$

(Geopolymer backbone)

The positive charge cation of the alkali (Na, K) balances the negative charge on Al in the geopolymer.

2.2 Geotechnical site investigations for dredging and land reclamation works

Understanding soft soil behaviour in a geotechnical context is complex, as the geotechnical properties of soft soil change with its moisture content and applied stress. Mitchell (1986) has reported geotechnical professionals have very advanced analytical capabilities, but, have inadequate abilities to predict actual field behaviour of soils. Dredging processes disturb the natural soil, change its stratification, structure and water content. According to Stallebrass et al. (2007), the behaviour of a given soil is determined by stresses, its water content, and structure. Whereas, Mitchell (1986) noted that soils are not inert materials; soils change with time and environmental conditions.

Dredging and land reclamation industry is characterised as a highly professional, capital intensive and risky industry, where, variations in soil and rock characteristics contribute significantly to project cost overruns, disputes and delays (Kinlan 2014). For instance, for a large cutter suction dredge (CSD) that is excavating a rock material, 15% increase in rock quality designation (RQD) reduces the hourly production rate of the dredge vessel by 50% as shown in Figure 2.4 (Kinlan and Roukema 2010) .

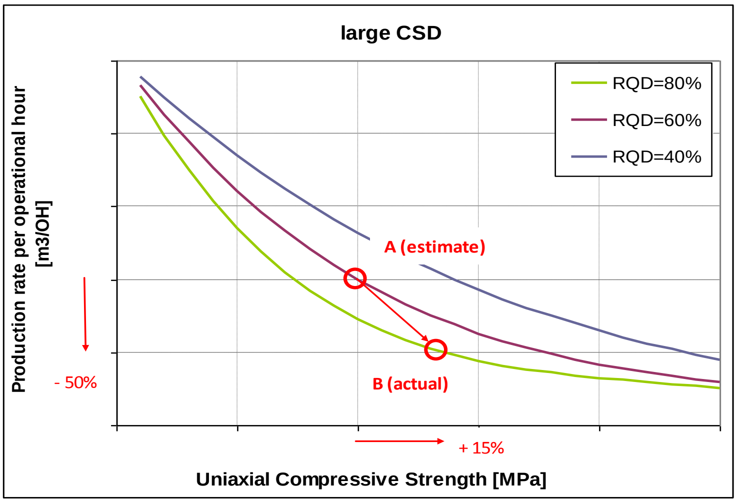


Figure 2.4 - Rock quality designation variations versus hourly production rates of large cuter suction dredge (Kinlan and Roukema 2010).

For a dredging project excavation task is always on the critical path of project construction program, as such any delay in excavation activity has an impact on the overall duration of the entire dredging project. Thus, successful design, tendering and execution of a dredging project require adequate knowledge of dredging site subsurface conditions, beside bathymetric and environmental parameters in which dredging vessels will be operating (PIANC 2000). According to PIANC (2014), in-situ soil geotechnical parameters that are essential for dredging works are those which assist in determining the optimal type of dredging plant to be used and help in identifying options for transporting, unloading, and using/ disposing of dredged material.

Design and construction of land reclamation project require knowledge of geotechnical properties of subsurface soil underneath the land reclamation site and the land reclamation fill material. Geotechnical site investigations prior to and post land reclamation works are necessary for land reclamation project planning, reclaimed ground improvement techniques selection, and foundation design (Cao 2003). Soil investigations prior to land reclamation works are usually undertaken to determine the geotechnical characteristics of the material to be dredged as well as conditions of subsurface formation that underlain the land reclamation site. Whereas, the post land reclamation geotechnical site investigations works are undertaken to assess the bearing capacity, consolidation, settlement of the fill material, to select optimum ground improvement measures, and foundation type (van't Hoff and van der Kloff 2012). Post land reclamation geotechnical investigations also answer the questions of reclaimed land stability and revetment walls safety against soil liquefaction and mud waves. Jaditager and Sivakugan (2016) have reported that offshore geotechnical site investigations at the dredging project site determine the dredgeability, and suitability of the dredged material to be used as a fill material for land reclamation purposes.

2.2.1 Objectives of geotechnical site investigations for dredging and land reclamation works

The geotechnical site investigations for dredging projects are undertaken to obtain the most comprehensive and accurate estimates of the subsurface profile and dredgeability properties of soil material to be dredged (Spigolon and Baker 1993). The material to be dredged information that is obtained from the geotechnical site investigations help selection of appropriate dredging plant, estimate production rate and project cost as shown below on Figure 2.5.

Site investigations → soil/rock properties

Soil /rock properties → dredging equipment

Dredging equipment → dredging production

Dredging production → dredging method to be used

Dredging method → dredging project duration / cost

Figure 2.5 -The influence of dredged material properties on dredging processes (ISSMGE 2005)

The objectives of the geotechnical site investigations for dredging and land reclamation works can be achieved by evaluating physical and mechanical properties of material to dredged, as well as its volume and distribution. The physical and mechanical properties of material to be dredged define dredgeability, and dredged material suitability for land reclamation (International Society for Soil Mechanics and Geotechnical Engineering 2005). To satisfy the necessary dredging and land reclamation site geotechnical requirements, soil and rock parameters outlined on Table 2.1 below are to be investigated.

Table 2.1 - Basic soil parameters required for dredging and land reclamation works (ISSMGE 2005).

Dredging and land reclamation application	**Material to be dredged**		
	Clay	**silt, sand or gravel**	**rock**
Excavation method and production	grain size, organic content, gas content, unit weight, Atterberg Limits, water content and undrained shear strength	grain size, angularity, carbon content, and density	rock quality designation (RQD), water absorption, unit weight, strength and mineralogy
Transport method	gas content, unit weight, Atterberg Limits, water content, and undrained shear strength	grain size, density, particle unit weight and mineralogy	unit weight of solid blocks, unconfined compressive strength (UCS) and mineralogy
Land reclamation fill material	Compressibility, void ratio, consolidation and permeability	Grain size, angularity and density	UCS, RQD, water absorption, unit weight and mineralogy

Selection of appropriate geotechnical soil properties is essential for accurate prediction of the anticipated degree of consolidation and settlement of the land reclamation fill material and the underlain natural soil layer (Ganesalingam and Sivakugan 2013). The intended usage of the reclaimed land and its performance requirements will determine the geotechnical site investigations for land reclamation works and soil parameters to be investigated. Soil properties that define its strength, stiffness, density and permeability are important for borrow / material to be dredged site. Whereas, soil parameters that are related to soil settlement, bearing capacity, stability and liquefaction potential are characteristics that are important for the land reclamation site (van't Hoff and van der Kloff 2012).

The main objectives of the geotechnical site investigations for dredging and land reclamation works are to establish the following:

- Volume and distribution of subsurface material to be dredged;
- Physical and mechnical properties of materail to be dredged to guide the dredging processes of excavation, loading of dredged material, transportation and unloading;
- Dredgability of the material to be dredged;
- Transportability of dredged material;
- Environmental impact of the dredging processes;
- Slope stability , slip cricle analysis and liquefaction potential of the reclaimed ground;
- Reclamation land fill material stiffness, consolidation duration and long term settlment; and
- Ground improvement strategy.

2.2.2 Scope of geotechnical site investigations for dredging and land reclamation works

Like any other civil engineering project, the geotechnical site investigations for dredging and land reclamation works comprise field works and laboratory testing. Scope of offshore geotechnical field investigations for dredging works includes: bore holes, cone penetration test, vibrocoring, standard penetration test (SPT) and collection of undisturbed and disturbed soil samples. Whereas, laboratory testing comprises sieve analysis/hydrometer, Atterberg limits, unconfined compressive stress, undrained shear strength, carbonate content, particle shape and one-dimensional consolidation (Oedometer) test (Jaditager and Sivakugan 2016).

For land reclamation works, the field investigations include testing and in-situ consolidation settlement monitoring. Reclaimed land in-situ monitoring includes settlement gauge and piezometers. Whereas, settling column test, sieve analysis/hydrometer, strength, compressibility and consolidation are some of the soil laboratory testings that are required for land reclamation works.

2.3 Dredging and land reclamation at the Port of Townsville

Located on the Cleveland Bay of tropical North Queensland, the Port of Townsville links northern Australia’s trade to the world. The Port of Townsville is connected to the national shipping routes by a 13 km long and 92 m wide dredged channel (Port of Townsville 2012). Like other ports around the world, in order to improve navigational safety of vessels and to cater for larger ships with deeper draughts, the Port of Townsville conducts maintenance and capital dredging works. The port's capital dredging campaigns over the last forty years has resulted in deepening and widening of the existing inner harbor basin and access channels and development of the outer harbour for berth 11 (Jaditager et al. 2015a). Beside capital dredging, the Port of Townsville also conducts annual maintenance dredging campaigns to remove sediments that accumulate via natural processes in the navigation channels and swing basin.

Since its establishment in 1860's, the port of Townsville has undertaken series of progressive developments in response to trade demands and ship sizes increase. With growth in trade throughput also, the need for expansion in port infrastructure has increased and led the Port of Townsville to start land reclamation to cater for the required infrastructure. The Port of Townsville's capital and maintenance dredged material is pumped in slurry form into containment ponds at port's eastern reclamation area and left to undergo sedimentation and self-weight consolidation to form land reclamation fill material. The beneficial use of dredged mud enabled Port of Townsville to reclaim approximately 100 hectares of land over the last three decades (Jaditager et al. 2015b). About 50% of the reclaimed land is already used for port infrastructure. The remaining half is undergoing self-weight consolidation processes to achieve trafficable conditions that are essential for commencement of soil stabilisation and ground improvement works.

2.3.1 Capital dredging at the Port of Townsville

Over the years, vessel size, trade demands and shipping trends have changed remarkably. The new vessels' increased draft requirements have triggered capital dredging to upgrade the dimensions of the navigation channels, turning basin and berth pockets at the Port of Townsville (Figure 2.6).

Figure 2.6 – Backhoe dredge deepening berth 7 pocket – the Port of Townsville (2015)

Beside the navigation channel and turning basin require continuous widening and deepening to keep up with the new ships that have deeper draughts, capital dredging works are also necessary in cases of new berths construction. In the early 1970's capital dredging works were undertaken to deepen the port's access channels and swing basin to accommodate the large oil tankers associated with Queensland Nickel Refinery (Service 1993). During the 1980's to 2000's the Port of Townsville conducted capital dredging to meet the increased draft requirements for the new shipping lines that were introduced by the new commodities such as nickel ore and cement. Defence, cruise ships and navigational safety improvements were behind the strategic upgrading that were occurred in the port's access channels and berth pockets since year 2000 (Jaditager et al. 2015a).

Guided by the geotechnical properties of soil to be dredged and dredged material placement alternatives, the Port of Townsville uses various dredging methods/plant for its capital dredging projects. Cutter suction, backhoe and grab dredges are predominately utilised by the port for its capital dredging campaigns. The cutter suction dredge deploys a rotary cutter-head to disturb the sea bed material and suction to remove the loosen material. Then the high-water content dredged material is pumped into reclamation containment ponds via a submerged, floated and land based dredged material pipeline. For mechanical (backhoe or grab) dredging method, a barge mounted long reach backhoe excavator or grab dredge with a clamshell bucket excavates the sea bed material and load the excavated material into a separate barge for transportation to a dredged material pump out point. Since Queensland State Government's Sustainable Ports Development Act 2015, all the dredged material derived from the Port of Townsville's capital dredging campaigns has to be brought ashore for land reclamation purposes (Queensland Government 2015).

2.3.2 Maintenance dredging at the Port of Townsville

The Port of Townsville is located in Cleveland Bay, faces Magnetic Island, and borders the Great Barrier Reef Marine Park at its seaward limit line. Navigation access to the Port of Townsville is via the outer Sea, Platypus and Ross River Channels. In order to maintain the harbor basin and approach channel depths for the navigational safety of the vessels against the natural accumulation of marine sediments, the port conducts regular annual maintenance dredging campaigns (Jaditager et al. 2014). In addition to the regular annual maintenance dredging, the Port of Townsville conducts emergency maintenance dredging in cases where large quantities of sediments are mobilized and deposited in port waters by cyclone or major flood events. Bathymetric surveys are conducted in quarterly basis and post major flood or cyclone event to monitor channel siltation and navigable depths. Analysis of historical maintenance dredging records showed average annual maintenance dredging volume at the Port of Townsville has been in the order of 95,000 cubic meters per year (the Port of Townsville 2011).

Whilst the maintenance dredging is a common requirement for many ports and harbours around the world, the Port of Townsville is special in relation to sediment quantities, frequency of maintenance dredging and sensitivity of the receiving environment. The Port of Townsville is geographically located at the Cleveland Bay where the wind-induced currents have significant influence on sediment transport during dredging activities (the Port of Townsville 2013). Moreover, the port is situated at the mouth of the Ross River and Ross Creek, the two primary waterways in the Townsville region; these two waterways pour sediments from the wider Townsville catchment area into the port waters every wet season.

According to Jaditager et al. (2014), quantities and distribution of the accumulated sediments throughout the port area defines maintenance dredging method and the associated type of dredge vessel to be used in dredging campaigns. The Port of Townsville uses grab dredge for maintenance dredging of Ross Creek area that has characteristics of shallow draught, tight corners and smaller volumes of sediments accumulation. For the inner harbor, platypus channel, sea channel and outer harbour areas with open basin, continuous long runs, deep waters and substantial amounts of sediments to be dredged, large trailer suction hopper dredge (TSHD) is ideal. Ross River channel has a shallow depth of minus 3 meter lowest astronomical tide (LAT) that is only can accessible by small size dredge, therefore, a small size cutter suction dredge (CSD) is used to undertake the maintenance dredging of Ross River Channel. Maintenance dredged material that is derived from the Port of Townsville waters can be placed on the designated ocean placement site or can be brought ashore as a fill material for land reclamation (Figure 2.7).

Figure 2.7 – Maintenance dredged material placement into land reclamation containment pond – eastern reclamation area the Port of Townsville (2017)

2.3.3 Land reclamation works at the Port of Townsville

Infrastructure Australia and National Transport Commission (2010) has reported Australia's ports and related landside logistics face major challenges from growth in trade, recommending a nationally coordinated approach to future planning and development of ports and freight infrastructure. Like most of other Australian ports, land scarcity around the Port of Townsville's compound led the port to adopt a land reclamation strategy as the preferred solution over other dredged material disposal options.

Land reclamation is a complex process and comprises a number of steps. Land reclamation works at Port of Townsville involves seabed preparation, construction of bund and revetment walls which involves the installation of rock walls into the ocean. The bund walls, reclamation ponds partitions and weir box positions are designed in a way that the greatest possible settling time is permitted for the dredged mud slurry to settle prior to the discharge of tail water back into the ocean. The dredged material containment ponds construction is followed by dredged material placement, dewatering, reclaimed land geotechnical site investigations and soil improvement works. The land created by reclamation works will keep the port efficient, sustainable and competitive, as it will cater for port infrastructure expansion that is driven by waterborne trade throughput growth, and the accompanied changes in shipping trends.

Since early 1980s, the Port of Townsville has reclaimed over 100 hectares of land using its maintenance and capital dredged material and planning to reclaim another 110 hectares of land over the next thirty years (Jaditager et al.2014). Figure 2.8 below shows the location of the Port of Townsville and the land that was reclaimed over the years.

Figure 2.8 - Location of the Port of Townsville and aerial view of its eastern reclamation area

Queensland State Government's Sustainable Ports Development Act 2015 calls for all capital dredging material derived from Queensland priority ports of: High Point, Abbot Point Gladstone and Townsville must be brought ashore (QLD Government, 2015). This QLD government sustainable ports development act dictates more land reclamation works to be undertaken at the Port of Townsville in order to accommodate the dredged material anticipated to be generated during the Port's future capital dredging campaigns.

To cater for dredged material to be derived from its future capital and maintenance dredging campaigns, the Port of Townsville is planning to increase the dredged material receiving and storage capacity of its eastern reclamation area. As reclaimed by soft dredged material, the Port of Townsville's eastern reclamation area is anticipated to take around twenty-five to thirty years to achieve 90% of its primary consolidation settlement with its self-weight consolidation alone (Jaditager et al. 2015b). To expedite the consolidation settlement, the Port of Townsville employed surcharging, lime stabilisation, cement stabilisation, and stone column soft soil stabilisations methods. The ground improvement means that were applied on the Port of Townsville's reclaimed land has resulted in different improved ground performances at different costs.

2.4 Soft dredged material stabilisation methods

The concept of soft soil stabilisation is as old as the construction industry. Chmeisse (1992) has reported soil stabilisation is being practiced at least for 5000 years. There were many ancient civilizations, including Chinese, Roman, and Incas in South America used different soil improvement techniques to improve soil under their roads, castles and worship places. Some of the buildings and roadways which were constructed on such stabilised soft soil during those ancient times are still standing today (Vitton 2006).

Reclaimed land areas are in rapid growth around the world. Growth in world's population, improvement in living standards and human attraction to living in coastal areas has led to land reclamation. Some land reclamation projects use high quality fill material; where in other cases soft fill material is used to create more land for residential and infrastructure expansions. Subsequently, various types of infrastructure such as ports facilities, industrial complexes, and airports have been constructed on reclaimed land to meet the increasing demands of development (Porbaha et al. 1999). Land reclaimed with soft fill material such as dredged mud is anticipated to take decades for primary consolidation settlement to complete by reclaimed ground's self-weight alone without ground improvement means. This typical lengthy waiting time is always a major constraint to the reclaimed land utilisation and meeting development time lines.

To accelerate the primary and secondary consolidation settlements of the land reclamation fill material and to increase its stiffness, there are several soil stabilisation methods that are currently applied. Most of soil stabilisation means that are widely used to stabilise naturally occurred soft soil are also applicable to soft ground that is reclaimed using soft dredged material as structural fill. These ground improvement techniques address the undesirable geotechnical properties of lengthy consolidation duration and excessive settlement that characterise land reclaimed by soft dredged material. The selection of the reclaimed ground improvement strategy is considered against factors such as: the functional requirement of the reclaimed land, the geotechnical properties of the fill material and the underlying subsurface, the development time lines and the associated cost.

The suitability of a dredged material stabilisation method is determined based on the followings:

- The intended load to be supported by the improved reclaimed ground;
- The acceptable amount of the post construction settlement;
- Sensitivity of the structures to be constructed on the improved reclaimed ground to total and differential settlement;
- Cost and duration of the ground improvement method;
- Availably of material, ground improvement plant, and skilled workforce; and
- Environmental footprint of the nominated ground improvement method.

In the land reclamation literature, wide range of research studies was conducted to optimise the ways to accelerate the consolidation settlement and to improve stiffness of land that is reclaimed using soft dredged material. Although each soft dredged material stabilisation project has its own soil conditions and loading requirements, the geotechnical properties of stabilised dredged material are usually the determinants of soil stabilisation method used. Performance of the stabilised dredged material, cost effectiveness, reduced environmental impact; and sustainability of the method are some the factors that influence the selection of soil stabilisation technique (Jegandan et al. 2010).

According to Beena (2010), soft soil improvement techniques generally increase adhesion between soil particles, densification and reinforcement to achieve one or more of the following:

- Increased bearing capacity to improve stability,
- Reduced deformation settlement due to compressibility or distortion of the soil mass,
- Reduced susceptibility to liquefaction, and
- Reduced natural variability of soils

The dredged material stabilisation as part of the wider soft soil improvement industry, it has its own specification, best practice and application manual that are available for port authorities and land reclamation practitioners. Dredged material stabilisation literature shows chemical admixtures, electrokinetic, surcharging, prefabricated vertical drains, and stone columns or combination of these means are the most employed. The details of these above mentioned dredged mud stabilisation techniques are outlined in the following sections 2.4.1 to 2.4.6.

2.4.1 Dredged material stabilisation with chemical admixtures

Mixing soft soils with stabilising chemical agents or binders has become a well-established technique for improving the geotechnical properties of soil by increasing its bearing capacity and reducing settlement due imposed load (Hird and Chan, 2008). Cement and lime are among the most widely employed admixtures that are used for improvement of geotechnical properties of soft soils (Rekik and Boutouil 2009). Industrial byproducts are also used in lieu of Portland cement as soil stabilisation additives. The industrial byproducts binders have advantages of cost effectiveness, reduced environmental footprint, enhanced durability performance, and increased range of application (Jegandan et al, 2010).

Soil stabilisation with admixture is a process of altering the physicochemical properties of the soil particles by changing the particular distribution, orientation and particle to particle relationship (Salehi and Sivakugan, 2009). It entails mixing of soft soil with suitable stabilising agent which may be in dry or liquid form to produce stabilised dredged material that has more desirable geotechnical properties. The usual liquid dredged material additives could be grout mixtures of cement, where the dry admixture are lime, Portland cement, fly ash and granulated blast furnace slag or combination of two or more of these mentioned soft soil stabilisation admixtures.

During the last four decades, dredged material stabilisation with admixtures and its resulting performance have been extensively studied worldwide. Calmano et al. (1985), Broms (1986) , Locat et al.(1996), Kassim and Huey (2000), Wang (2002), Chew et al. (2004), Wilkison et al. (2010), Rao et al.(2011), Makusa et al.(2012); Santoso et al. (2013) and Chan et al .(2013) are some of the research works in the area of dredged mud stabilisation by admixtures. The following are some general conclusions that can be drawn from these previous dredged materials with admixture studies:

- Admixtures are used to reduce the settlement of the dredged material as well as improving its strength properties.
- Field investigations, laboratory testing, and numerical analysis methods are followed to assess the engineering properties of the dredged material that is stabilised by chemical admixtures.
- Dredged material stabilisation mechanisms, geotechnical characteristics, mineralogy and microstructure of the stabilised dredged material, and factors that influence the effectiveness of the stabilisation by admixture are largely studied by the researchers.
- Hydration, ionic exchange between dredged material and the additive or pozzolanic reaction are the main stabilisation mechanisms that control the dredged mud stabilisation with admixtures (Table 2.2).
- During hydration process, additive such Portland cement or lime reacts with the water in the dredged material pores, where, for ionic exchange, metallic ions on the surface of dredged mud particles exchange with opposite ions that are produced by the admixtures.
- During the pozzolanic reaction, alkali hydroxide released by the admixture into the dredged material pore water reacts with pozzolanic component (silicate and aluminate) in the dredged mud to form a cementitious binder.
- Stabilised dredged material characteristics of coefficient of volume compressibility (m_v), permeability coefficient (k), coefficient of consolidation (c_v), unconfined compressive strength (UCS), mineralogy and microstructure are commonly used to assess the effectiveness of the dredged material stabilisation with admixtures.
- Site conditions, mixing method, and dredged material homogeneity influence the mechanical properties of the stabilised dredged material.
- Though geopolymer application research is advancing, it is noted there is no geopolymer stabilisation of dredged material recorded in the published literature.

- Most dredged material stabilisation effort was emphasised on post formation of dredged mud sediment skeleton, with little effort went towards stabilising the dredged material while it is in its slurry form.
- Most of the existing dredged material stabilisation methods has the limitations of it has to applied after the land reclamation material is dewatered or the reclaimed ground has gained sufficient consolidation and strength to sustain construction traffic which is tedious and time-consuming process (Figure 2.9).

Table 2.2 – Dredged material stabilisation with some admixtures and the corresponding mechanisms (Druijt 2016)

Admixture	Reaction with	Stabilisation mechanism
Cement	pore water and soil particles	hydration, ionic exchange and pozzolanic reaction
Lime	pore water and soil particles	hydration, ionic exchange and pozzolanic reaction
Fly ash	soil particles	pozzolanic reaction

Figure 2.9 – Dredged material stabilisation with lime at the eastern reclamation area – the Port of Townsville (2007) (image courtesy of the Port of Townsville)

2.4.2 Electrokinetic stabilisation of dredged material

Electokinetic stabilisation of clayey soil combines processes of electroosmosis and chemical grouting (Baker et al 2004). Electrokinetic stabilisation is conducted by application of direct electrical current to the dredged material through electrodes. The applied electrical current causes flow of the soil pore water from anodes to cathodes due to the effect of electroosmosis process and soil particle movement due to electromigration (Malekzadeh 2016). The flow of pore water reduces both the water content of the dredged material and pore water pressure, and increases effective stress which in turn improves the consolidation characteristic of the dredged material. Pore water cation and onion distribution, dredged material water content and cation distribution influence the degree of electromigration during electrokinetic stabilisation. Elctrokinetic stabilisation is environmentally friendly and time efficient soft soil stabilisation method that improves shear strength, compressibility and permeability of the stabilised soil. However, electrokinetic soil stabilisation has disadvantages of unknown electrochemical reactions that change the chemical properties of the stabilised soil and lack of standard design guidelines.

2.4.3 Dredged material stabilisation with surcharge preloading

Surcharge preloading is a cost-effective method of dredged material stabilisation by the dead load of a soil mount (Figure 2.10). According to Krizek (2004), surcharging offers a time-tested procedure for accelerating the consolidation and dewatering of soft soil material and increases its strength gaining rate.

Figure 2.10 – Surcharging of eastern reclamation area – the Port of Townsville (2017)

The surcharging soil mount is usually easy handing soil material such as sand or clayey sand that accelerates the primary consolidation settlement of the land reclamation fill material to allow early utilisation of the reclaimed land. For reclaimed land stabilisation by surcharge to be successful, the surcharge load is to exceed the intended future load that is to be applied on the reclaimed ground. The design of amount of surcharge required is determined by the load that is anticipated permanent structures will impose on the reclaimed ground, and the amount of secondary consolidation of the land reclamation fill material. For land reclaimed for port infrastructure, it is anticipated loading is to be as result of office buildings, heavy duty pavement such as container yard, chemical storage tanks, railways and road networks.

The surcharging accelerates the primary consolidation of the land reclamation fill material by increasing its pore water pressure, which in turn lead to faster excess pore water dissipation e expediting the consolidation settlement of the reclaimed ground. For soft soil surcharge preloading application to be effective in eliminating all or most of the primary consolidation settlement, there are several soil parameters that are needed to be determined and understood. Soft soil characteristics of maximum past pressure (σ_c), coefficient of consolidation (c_v), compression index (C_c), seconadary compression index ($C_\propto$), and undrained shear strength (s_u) are used in design and application of surcharge preloading (Mohamed 2008). Knowledge of reclaimed ground subsurface profile and the geological history of the land reclamation site are also useful for refining the design and successful application of dredged material stabilisation by surcharge preloading. Although it is a cost effective method of reclaimed land stabilisation, the surcharge soil mount requires to be remained in place for sufficient time to be effective in settlement reduction.

2.4.4 Dredged material stabilisation with prefabricated vertical drains (PVD)

Prefabricated vertical drains soft dredged material stabilisation system, also known as wick drains, comprises prefabricated plastic cores that are covered by a permeable geotextile material. A retractable steel mandrel mounted on an excavator is used to install prefabricated vertical drains into a saturated soft land reclamation fill material (Figure 2.11). Prefabricated vertical drains accelerate the primary consolidation of the soft soil by improving its drainage system (Arualrajah et al. 2008). It provides alternative shorter excess pore water drainage paths as the consolidation rate of a saturated soft soil layer is function of the length of its drainage path. Beside accelerating the primary consolidation of the reclaimed fill material, the prefabricated vertical drains also has advantage of limiting the pore water pressure build up that may cause liquefaction of the soft land reclamation fill material.

Figure 2.11 – Reclaimed land stabilisation with Prefabricated Vertical Drains – Chek Lap Kok airport land reclamation, Hong Kong (Kolman 2012)

Research showed the design of prefabricated vertical drains system entails assumptions of soft soil properties, and various drainage conditions and iterative procedures that fully appreciate soft soil consolidation process. Prefabricated vertical drain diameter of influence zone, length, drain spacing and soil permeability are among the parameters that guide the design of prefabricated vertical drain system. To eliminate cumbersome iterative procedures that are used to determine prefabricated vertical drain diameter and spacing, Rujikiatkamjorn et al. (2015) has developed prefabricated vertical drains design charts. The design chart considers both vertical and horizontal drainage using equivalent drain diameter as an independent variable to obtain the relevant drain spacing.

2.4.5 Dredged material stabilisation with stone columns

The main idea behind stone column stabilisation of soft dredged material is to penetrate and replace loose and soft soils with dense coarse material that lead to a faster dissipation of pore water pressure, which in turn expedite the land reclamation fill material consolidation process.Stone columns system comprises compacted stone column with diameters varies between 750 mm to 1200 mm. Stone columns installation is conducted by penetrating the soft ground required to stabilised using excavator mounted vibrating poker or equivalent, Then the stone is pushed into the hole that was generated by the poker. According to Mokhatari and Kalantari (2012), there are two main stone columns installation methods, namely, top feeding system (Figure 2.12) and bottom feeding systems. Both the top feeding and the bottom feeding methods use excavator with vibrating probe to feed the stones into soft ground. The only difference between the two methods is, the top feeding system starts stone feeding from the ground surface down, where the bottom feeding system starts stone feeding from the bottom of the soft fill material layer up to the reclaimed ground surface as shown on Figure 2.13.

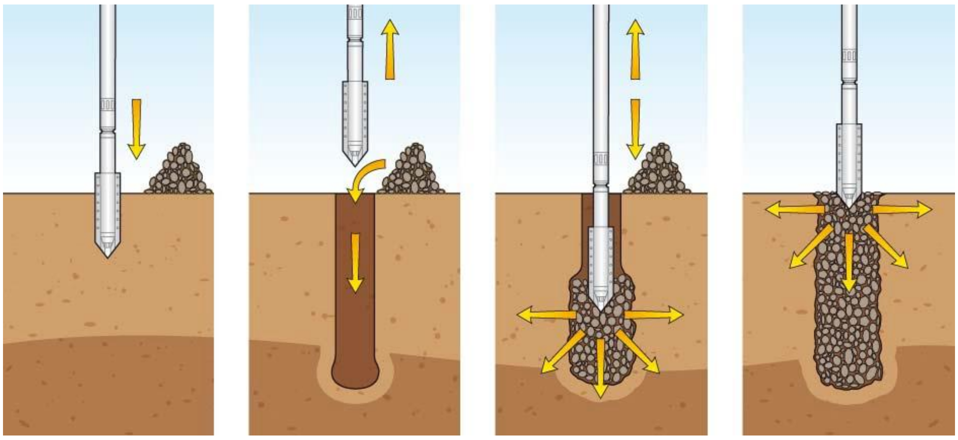


Figure 2.12 – Schematic of top feeding stone column installation (Mokhatari and Kalantari 2012)

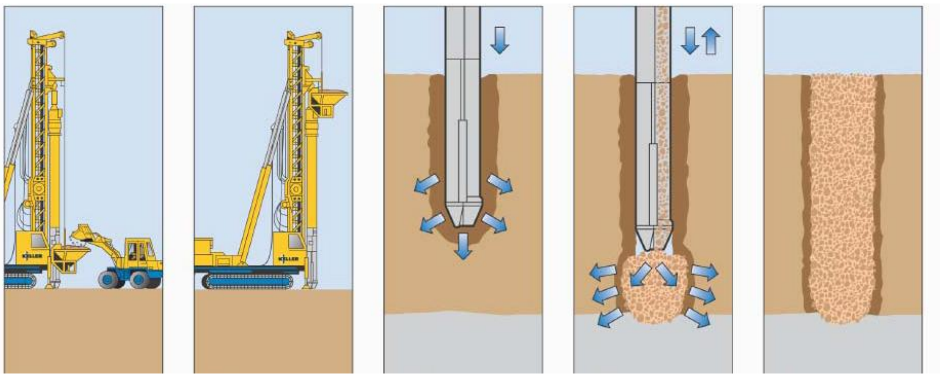


Figure 2.13 – Schematic of bottom feeding stone column installation (McCabe et al. 2007)

Stone columns improve the engineering properties of soft dredged material by reinforcing the dredged material, providing better pore water drainage paths to reduce settlement, increase consolidation rate and enhance the overall shear strength of the stabilised dredged material. Reclaimed ground profile, geology and loading condition are the determinants of the design of the stone column to be used to improve the geotechnical properties of a soft reclaimed ground. However, as stone column design is an iterative process, normally pilot studies on small area of the reclaimed ground to be treated are conducted to accurately determine the parameters that drive the efficiency of stone columns soil improvement.

The aim of the stone columns soil stabilisation pilot study is to determine the following parameters:

- Diameter of the stone columns and quantity of material to be incorporated in each column;
- Optimized number of stone columns installation phases;
- Resting time between phases;
- Optimized grid spacing of the stone columns group;
- Best installation method and energy to be used for stone columns installation;
- Average settlement generated by the stone columns soil stabilisation; and
- Characteristics of the improved reclaimed ground post stone columns installation.

Beena (2010) has recommended geotextile encasement of the stone columns in cases of the stone columns are installed into very soft soil, where the lateral confinement that to be provided by the surrounding very soft soil material is not sufficient.

2.4.6 Limitations of some of the existing dredged material stabilisation methods

Table 2.3 Limitations of some of the existing dredged material stabilisation methods

Dredged material stabilisation methods	Disadvantages
Chemical admixtures	• Lack of standard methods of testing and quality control. • Require intensive site investigations prior to application. • High cost of chemical admixtures and ground improvement plant.
Electrokinetic	• Unknown electrochemical reactions that cause unknown changes to soil chemical properties. • Lack of standard design guide lines.
Surcharging	• For very soft soil, surcharge has to be applied in stages to maintain soil stability. • Surcharging needs to be in place for excessive amount of time to achieve the required degree of consolidation. • It may need to be applied in combination with prefabricated vertical drain to be effective
Prefabricated vertical drains (PVDs)	• Require specialised equipment and the associated high plant mobilisation cost. • Prefabricated vertical drains installation causes soil disturbance and soil stability issues.
Stone columns	• Undergo horizontal deflection and require lateral support from the surrounding soil if installed in very soft soil. • Require specialised equipment

Chapter 3: Dredged mud slurry stabilisation with fly ash-based geopolymer binder-material and method

3.1 Dredged mud slurry stabilisation with fly ash-based geopolymer - experimental study

The published dredged material stabilisation literature shows most of soft dredged material stabilisation effort is focused on post dredged mud sediment formation by sedimentation and self-weight consolidation and drying to moisture content around 250%. This is attributed to the fact that high water content nature of the fresh dredged mud slurry makes the application of most the current soft dredged material impossible or not feasible. Stabilising soft dredged mud slurry with admixtures would lead to different sedimentation and consolidation behaviours when the dredged mud particles in the suspension settle to form a soil.

This research postulates the potential of the fly ash-based geopolymer binder to coat the dredged mud particles in soft dredged mud slurry, thereby alter the sedimentation and the consolidation behaviour of the resulting stabilised dredged mud sediment. In this experimental study the feasibility of stabilising the Port of Townsville's dredged mud slurry with newly synthesised fly ash-based geopolymer binder as an alternative stabilisation method is investigated. This section of the dissertation describes the experimental study method; reconstitution and remoulding of the Port of Townsville dredged material, as well as dredged material index and physical properties determination. Geopolymer materials properties, geopolymer synthesisation mix designs, alkali activator solution preparation, fly ash-based geopolymer binder synthesisation and dredged mud slurry stabilisation with the fly ash-based geopolymer binder are also discussed in this section of the dissertation.

3.1.1 The Port of Townsville dredged material

The dredged material used in this laboratory experimental study was excavated from depth of 1.2 m below surface level of the most seaward pond - eastern reclamation area - the Port of Townsville (Figure 3.1). The dredged material was excavated using an eight-tonne backhoe excavator. The most seaward dredged material containment pond from where the dredged mud sample was taken is considered to be the pond that contains the softest dredged mud. This particular dredged material containment pond receives the last sediment that settles from the tail water before it discharged into ocean via weir box.

Figure 3.1 – Dredged material excavation– eastern reclamation area -the Port of Townsville

3.1.1.1 Reconstitution and remoulding of the Port of Townsville dredged mud

There are difficulties in obtaining identical high-quality soil specimens that have known stress history and homogeneous properties for engineering testing. Sheeran and Krizek (1971) have advised to effectively study the engineering behaviour of cohesive soils, it is necessary to manufacture reproducible soil samples in controlled laboratory environment by consolidating a high-water content soft soil slurry. The extracted, the Port of Townsville dredged mud sample was transported to James Cook University - Geomechanics Laboratory Townsville, for examination and testing. The dredged mud sample was remoulded and reconstituted in seawater slurry at 400% water content Figure 3.2.

Figure 3.2 – Reconstituted the Port of Townsville dredged mud slurry before and after sedimentation

The reconstituting of dredged mud is also undertaken to simulate dredged mud slurry that is hydraulically placed into containment ponds to settle and self-weight consolidate to form land reclamation fill material as specified by Ganesalingam et al. (2011). The dredged mud sample was sieved via sieve mesh No. 8 (2.38 mm) to remove potential impurities and foreign objects such as pebbles and sea shell debris that usually come with dredged material. Atterberg limits, wet sieve and hydrometer analysis were carried out according to Australian Standards (AS 1289.3.1.1 to AS 1289.3.6.1 - 2009) methods of testing soils for engineering purposes.

The majority of land reclamation using soft dredged mud slurry projects are conducted by a trailing hopper suction dredge (THSD) or a cutter suction dredge (CSD). Both trailing hopper suction dredge and cutter suction dredge vessels rip and fluidise the in-situ marine sediment and turn it into high water content dredged mud slurry to facilitate dredging processes . Also, the detailed investigation of the sedimentation behaviour of dredged mud requires a dilute dredged mud-water mixture that would produce homogenous identical dredged mud sediment samples for laboratory testing.

Like most ports and waterways, the Port of Townsville conducts its maintenance dredging in annual basis. The actual maintenance dredged mud slurry that is derived from the Port of Townsville is usually a thin layer of soft sediments that are recently deposited into navigational channels and berth pockets. For the capital dredging, the dredge vessel fluidises the over-consolidated seabed sediment, turning it to about 400% to 500% water content dredged mud slurry, using rippers and high-pressure water jets that are attached to the drag heads. Ripping and fluidisation of seabed sediment is usually undertaken to optimise the dredging and the dredged material placement processes. From dredging perspectives, dredged material is more convenient to be handled as slurry rather than solids.

The only difference between the reconstituted dredged mud sample used in this study and the dredged mud slurry that is derived from actual dredging campaigns is the presence of pebbles and broken sea shells in the dredged mud slurry that was derived during actual dredging campaign. Whereas, for the reconstituted dredged mud samples, the pebbles and the broken shell were removed by sieving the dredged material via sieve No. 8 (2.38 mm). Although its weight is negligible compared to the overall weight of the specimen, the pebbles and broken shells are need to be removed. Ganesalingam (2013) has advised the existence of pebbles and broken sea shells in the oedometer specimens affect the homogeneity of the oedometer specimens and complicate applied stress - pore water dissipation rate relationship during the one-dimensional consolidation test.

3.1.1.2 Index and physical properties of the Port of Townsville dredged mud

In geotechnical practice, soil index properties are commonly used to discriminate among different soils or to distinguish the different states of the same soil (Terzaghi et al. 1996). Standard index property tests of Atterberg limits, specific gravity, and wet sieve and hydrometer analysis test were conducted to classify and describe the Port of Townsville dredged mud. The Port of Townsville dredged mud is classified as high plasticity silty clay. Table 3.1 below summarises the index and physical properties of the Port of Townsville's dredged material.

Table 3.1 - Index and physical properties of the Port of Townsville dredged mud

Property	**Value**
Liquid Limit (LL)	74%
Plastic Limit (PL)	32%
Plasticity Index (PI)	42%
Clay content	59.3%
Silt content	38.7%
Sand content	2%
Specific Gravity (G_s)	2.67

3.1.1.2.1 Atterberg limits

Atterberg limits are moisture content boundaries that define soil material consistency states; they give an indication of soil mineralogy and activity. Atterberg limits also correlate to strength and compressibility characteristics of the cohesive soft soil. Atterberg limits test was performed on the Port of Townsville's dredged mud to determine the ranges of its liquid limit, plastic limit and plasticity index. The Port of Townsville dredged mud was found to have Liquid Limit (*LL*) of 74%, Plastic Limit (*PL*) of 32%, and Plastic Index (*PI*) of 42%.

3.1.1.2.2 Specific gravity test (G_s)

Specific gravity of a soil material is defined as the ratio of the density of a given volume of soil material to density of an equal volume of distilled water. In soil mechanics, specific gravity of soil solids is an important parameter for calculating weight-volume relationships such as void ratio (Das and Sobhan, 2012). The specific gravity test revealed the Port of Townsville dredged mud has specific gravity (G_s) of 2.67.

3.1.2.3 Particle size distribution

The grain size distribution of a given soil mass is one of the defining characteristics that is used in classifying soils for engineering purposes. Australian Standard 1289.3.6.2 specifies sieve analysis and hydrometer methods for determination of soil grain size distribution in laboratory. Sieve analysis method is used for soil particles that are larger than No. 200 sieve size (0.075mm) and hydrometer analysis for soil particles that are finer than 0.075mm. To obtain full scale particle size distribution of soils that comprise both fine and coarse particles, wet sieve and hydrometer analysis are necessary. Wet sieve and hydrometer test were conducted to determine the particle size distribution of the Port of Townsville dredged mud. Figure 3.3 below shows the particle sizes distribution curve of the Port of Townsville dredged mud. The Port of Townsville dredged mud comprised 59.3% clay, 38.7 % silt and 2% sand as shown in above Table 3.1.

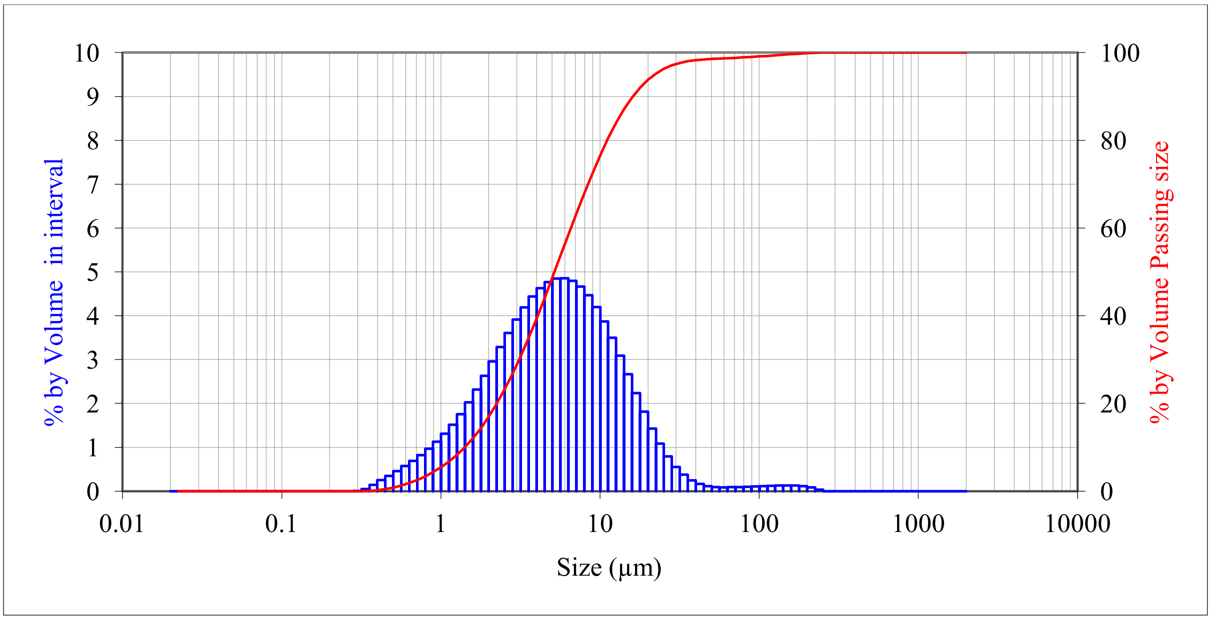


Figure 3.3 – Particle size distribution curve for the Port of Townsville dredged mud

3.1.2 Fly ash-based geopolymer material

Chemically reactive alkali soluble aluminosilicate source material such as fly ash or granulated blast furnace slag and alkali facilitator solution such as sodium hydroxide are required for geopolymer synthesisation. For this experimental study, fine grain, low calcium (class F) Gladstone fly ash was used as alumni-silicate source material. Whereas, the sodium hydroxide (NaOH) solution is used as alkali activator liquid to dissolve the fly ash spheres to synthesise the fly ash-based geopolymer binder. Both the class F fly ash and sodium hydroxide are readily available for purchasing from building products and chemical suppliers (Hardjito, 2005 and He, 2012).

There was no dredged mud slurry stabilisation with fly ash-based geopolymer binder specifications in the published literature. Therefore, the fly ash-based geopolymer material proportion, alkali liquid concentration, alkali liquid fly ash mixing ratio, mixing time, and the geopolymer synthesisation specifications that are used in geopolymer concrete industry are adopted for this experimental study.

3.1.2.1 Gladstone class (F) fly ash

Fly ash is chosen as source of silica and alumina for geopolymer binder formation for the fact that the fly ash-based geopolymer material exhibits favourable characteristics compared to other silica and alumina source. Fly ash-based geopolymer literature shows fly ash as a reactive aluminosilicate source material, it has the advantages of higher compressive and flexural strength compared to other reactive aluminosilicate source material such as metakaolin. Skvara et al. (2005) has concluded that fly ash-based geopolymer has properties of high strength, excellent resistance to corrosive action of salt solutions and high resistance to temperature. Whereas, Vickers et al. (2015) have advised the utilisation of fly ash in geopolymer formation provides sustainability and produce geopolymer material with improved physical properties. The fly ash is used as a secondary raw material for many industries for its commercial availability throughout most of the world (Hajimohammadi and van Deventer 2016).

Low calcium class (F) fly ash that was obtained from Gladstone coal fired power generation station – Queensland - Australia was used as a source of reactive aluminosilicate material for the fly ash-based geopolymer synthesisation.

Table 3.2 below presents the chemical composition of Gladstone fly ash.

Table 3.2 - Oxides composition of fine grade (class F) Gladstone fly ash

Oxide Compound	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	TiO_2	P_2O_5	Na_2O	K_2O
(Weight %)	51.1	27.0	13.0	3.4	1.4	1.4	1.1	0.72	0.72

3.1.2.2 Alkaline activator liquid

Khale and Chaudhary (2007) have advised in order to activate silicon and aluminium particles that are present in aluminosilicate source material, the fly ash, and a strong alkali material such as sodium hydroxide (NaOH) are required. Sodium hydroxide (NaOH) pellets at 98% concentration (Figure 3.5) that are dissolved into fresh water at 8 molars (320 grams / litre) was used as alkali activator liquid for the fly ash-based geopolymer binder synthesisation.

Hardjito (2005) has used the sodium hydroxide solution at 320 grams/litre to synthesize fly ash-based geopolymer that was used for geopolymer concrete. The specified alkali activator solution mix design produces fly ash-based geopolymer with optimum workability and binding properties.

Appropriate concentration of sodium hydroxide solution is vital in determination of the quality of the resulting fly ash-based geopolymer binder. The fly ash-based geopolymer binder parameters of density, silica and alumina leaching and the proportion of un-reacted fly ash sphere are driven by the sodium hydroxide solution concentration (Ibrahim et al. 2017). Figure 3.6 below shows sample of the sodium hydroxide alkali solution that was used for this experimental study.

3.2 Fly ash-based geopolymer binder synthesisation

To obtain appropriate mechanical properties and workability of the geopolymer binder, the geopolymer synthesisation time and material mix design similar to that was reported by Zhang et al. (2013) were used in this experimental study. The fly ash-based geopolymer material for this study was synthesised by mixing the alumina-silicate source material, the Gladstone - low calcium (class F) fly ash with the alkali activating solution for up to ten minutes as specified by Hardjito et al. (2005). To ensure homogeneity of the intended fly ash-based geopolymer binder, desk top mixer with whisk attachment was used to mix the alkali activator liquid dissolved fly ash. Figure 3.4 shows the synthesised fresh ash-based geopolymer binder.

Figure 3.4 - Fresh fly ash-based geopolymer binder

The mixing proportion of activating solution to the alumina-silicate source materials was 30% by weight (He 2012). Upon coming into contact with the sodium hydroxide (NaOH) alkali solution, the low calcium, class F fly ash dissolves into alkali solution by exothermic and geopolymeric chemical reactions. Dissolution of the class F fly ash (the aluminosilicate source material) by the sodium hydroxide alkali activator liquid was governed by exothermic chemical reaction (equation 3.1) that was described by Motorwala et al. (2013). Where, the subsequent creation of geopolymer gel in form of silicon and aluminium species was governed by geopolymeric chemical reaction as shown on equation 3.2.

Exothermic equation (releases heat):

$$\underset{\text{Fly ash}}{(SiO_2)_2 + Al_2O_3 + 4H_2O} \xrightarrow{NaOH} (Na)^{+} + \underset{\text{(Geopolymer precursor) (gel)}}{(OH)_3(\text{-Si-O-}\underset{\underset{(OH)_3}{|}}{Al}^{-}\text{-O- Si-O-})(OH)_3} \quad (3.1)$$

Geopolymeric equation:

$$(OH)_3(\text{-}\underset{\underset{(OH)_3}{|}}{Si}^{-}\text{-O-Al-O-Si-O-})\,(OH)_3 \xrightarrow{NaOH} (Na)^{+}\text{-}\underset{\text{(Geopolymer backbone)}}{(\underset{\underset{O}{|}}{Si}\text{-O-}\underset{\underset{O}{|}}{Al}^{-}\text{-O-}\underset{\underset{O}{|}}{Si}\text{-O-})(OH)_4} + 3H_2O \quad (3.2)$$

The first phase of the fly ash-based geopolymer material formation chemical reaction (i.e. the dissolution of fly ash) yields geopolymer precursor in form of a geopolymer gel. Where, the geopolymer backbone is formed during the second phase of the geopolymersation process that occurs by more dissolution, re-orientation and condensation processes. Although the fly ash-based geopolymer material has high temperature resistance, the fly ash-based geopolymer binder synthesization and the accompanied dredged mud slurry stabilisation with geopolymer binder were undertaken at ambient temperature range of 24 ± 3^{o} C (Jaditager and Sivakugan 2016).

3.3 Dredged mud slurry stabilisation with fly ash-based geopolymer binder

3.3.1 General

In dredging and land reclamation industry, soft dredged mud stabilisation measures are implemented to improve strength and stiffness, increase workability and to reduce shrinking and swelling of the clayey land reclamation fill material (van‘t Hoff and van der Kolff 2012). Improving reclaimed land fill material mitigates excessive settlement, reduce consolidation duration, prevent mud waves and slip failure of the reclaimed ground due to pressure to be imposed by the structures to be constructed on the reclaimed ground.

For soils that are formed by natural processes of weathering of rocks, transportation, deposition/sedimentation and self-weight consolidation, soil stabilisation techniques address the existing unfavourable geotechnical properties of these soft soils. However, for manmade soft grounds such as land reclaimed by soft dredged material, there is a chance to manipulate the microstructure of the intended land fill material that defines its compressibility and consolidation properties. The microstructure of to be formed land reclamation fill material can be controlled by influencing the sedimentation behaviour of the high water content fly ash-based geopolymer stabilised dredged mud slurry before it turns to dredged mud sediment. In other words, a proactive or early geotechnical intervention approach.

This experimental study has adopted this early intervention dredged mud slurry stabilisation approach by stabilising dredged mud while still in its slurry form in order to control the sedimentation behaviour of the geopolymer stabilised dredged slurry. The sedimentation behaviour of the fly ash-based geopolymer stabilised dredged mud slurry influences the microstructure, the compressibility and the consolidation characteristics of the stabilised dredged mud sediment. The selection of fly ash-based geopolymer as an alternative binder was motivated by its cost effectiveness; environmentally friendly nature and less sensitivity to the dredged mud slurry high-water content. The following section discusses the proposed dredged mud slurry stabilisation with fly ash-based geopolymer binder and the obtained results. The influence of fly ash-based geopolymer stabilisation on sedimentation, mineralogy, microstructure, and consolidation characteristics of the fly ash-based geopolymer stabilised dredged mud are detailed on chapters 4, 5 and 6 respectively.

3.3.2 Dredged mud slurry stabilisation with fly ash-based geopolymer binder -method

A fresh synthesized fly ash-based geopolymer binder (Figure 3.4) was added to 400% water content dredged mud slurries at 6%, 12% and 18% by weight. To ensure the dissolved silica (Si) and alumina (Al) species diffuse around the dredged mud particles, the fly ash-based geopolymer binder - dredged mud slurry mixtures were thoroughly stirred for five to seven minutes. The newly synthesised fly ash-based geopolymer binder was added to the dredged mud slurry well ahead of the 120 minutes geopolymer paste setting time that was reported by (Hardjito et al. 2008).Then, the untreated and the fly ash-based geopolymer stabilised dredged mud slurries were poured into identical Perspex cylindrical tubes of 100 mm inner diameter by 700 mm high to height of 600 mm as shown in Figure 3.5. For each Perspex cylindrical tube, a porous bottom cap with filter paper on its top face was bolted to the cylindrical tube's base plate. The filter papers are placed to prevent piping of dredged mud fines through the porous cap with the pore water when the dredged mud sediments are loaded. While the dredged mud slurries were undergoing sedimentation and self-weight consolidation, settling patterns and sediment-clear water interface height variation with elapsed time were noted.

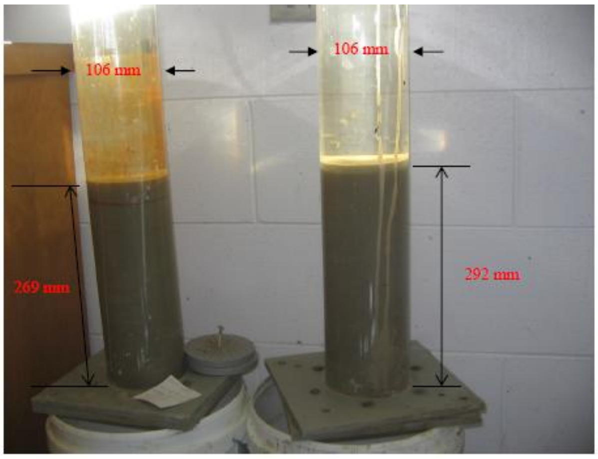


Figure 3.5 - From left to right, settling tubes of untreated and 6% fly ash-based geopolymer stabilised dredged mud slurries

Upon mixing with the dredged mud slurry, the fresh synthesised fly ash-based geopolymer gel coats surface of the clay particles in the dredged mud slurry. It is known in the geopolymer literature thatgeopolymers are characterised with high adhesion and film forming properties. The fly ash-based geopolymer gel coating increases the sizes of the dredged mud particles in the slurry, bringing them closer to each other, causing aggregation leading to flocculated soft soil settling behaviour that was discussed by (Imai 1980). Generally, dredged mud slurry stabilisation with admixture is less favourable for its excessively high-water content would dilute the stabilising agent as pointed out by Salehi (2009). However, this laboratory experimental study results suggests, it is feasible to stabilise high water content dredged mud slurry with fly ash-based geopolymer binder. One of the attributes of fly ash-based geopolymer binder, it is not sensitive to the high-water content nature of dredged mud slurry; in contrary, the polymeric chemical reaction that results geopolymer backbone produces water.

In practical application on land reclamation with soft dredged mud slurry projects, dredged mud stabilisation while at its slurry stage means potential of manipulating the sedimentation behaviour of the stabilised dredged mud slurry that influences the geotechnical properties of the final fill material. Ganesalingam et al. (2013) has proposed the settling behaviour of soft soil slurry influences homogeneity and consolidation characteristics of the final sediment. Upon completion of its sedimentation and self-weight consolidation processes, fly ash-based geopolymer stabilised dredged mud specimens where extracted and examined for mineralogy and consolidation characteristics and compared to those of untreated dredged mud sediment. The flocculation that was induced by the fly ash-based geopolymer gel coating the dredged mud particles in the slurry is believed to be the main mechanism that governs the dredged mud slurry stabilisation process.

3.3.3 On-site stabilisation of dredged mud slurry with fly ash-based geopolymer binder

The concept schematic on Figure 3.9 depicts the onsite stabilisation of dredged mud slurry with fly ash-based geopolymer. Stabilisation of dredged mud slurry with the fly ash-based geopolymer binder on land reclamation project site can be achieved by establishing geopolymer batching plant and a mixer adjacent to the dredged mud slurry pipe line. The geopolymer batching plant is to synthesise a fresh geopolymer binder by combining the alkali activator (sodium hydroxide NaOH) solution to the fly ash at a mix design of 30% by weight. For the mixer to thoroughly mix the fly ash-based geopolymer binder with dredged mud slurry before discharging it into to the land reclamation containment ponds. To store and handle the geopolymer formation material, a fly ash silo and sodium hydroxide liquid tank are to be installed and reticulated to the geopolymer batching plant. Bases of the geopolymer batching plant, the fly ash storage silo, the alkali activator liquid tank and the mixer to be attached to steel frame to facilitate bolting to concrete block and easy mobilization.

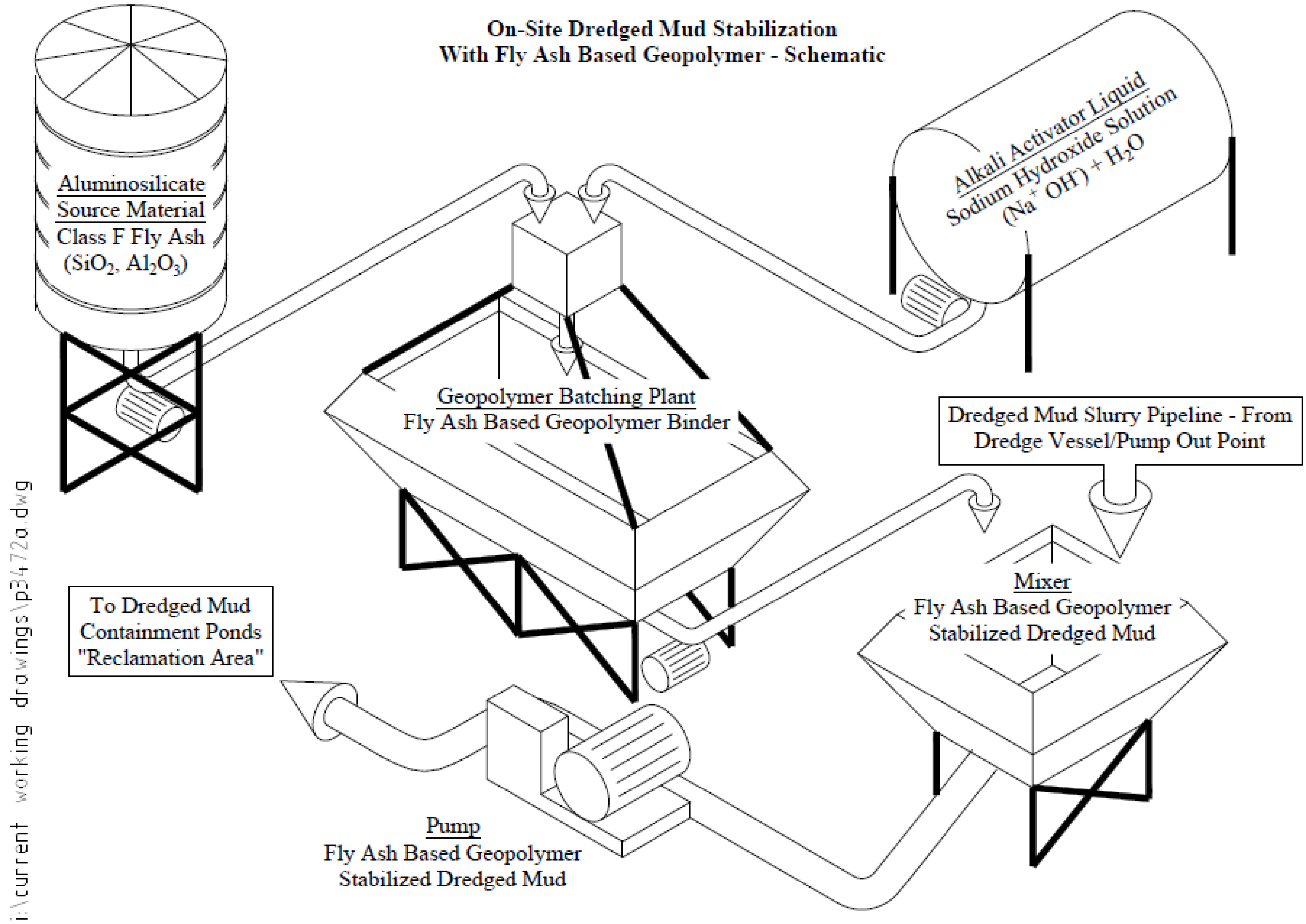


Figure 3. 6 - Concept schematic of on-site stabilisation of dredged mud slurry with fly ash-based geopolymer binder

3.3.4 Environmental impacts of dredged mud slurry stabilisation with fly ash-based geopolymer

During the dissolution of the fly ash in the sodium hydroxide solution and the geopolymersation chemical reactions, the geopolymer precursor dissolution, re-orientation and condensation processes releases free sodium ions (Na^+) into the surplus water (equation 3.2). On a land reclamation project site where fly ash-based geopolymer stabilised dredged mud slurry is used, the released sodium ions (Na^+) may adversely affect the tail water quality and increase its alkalinity (pH). In this laboratory experimental study, the tail water chemistry is measured using multi-parameter water quality device (Figure 3.10). The pH of the clear water that is accumulated on the top of the geopolymer stabilised dredged mud sediment was found to 8.1, knowing the pH of the seawater around the Port of

Townsville is 8.0. There is an increase of 0.1 on pH scale, which is attributed to Na^+ ion that was released as a by-product of the geopolymer formation process. However, pH reading of 8.1 is within 6.5 to 8.4 range that was nominated by the tail water chemistry guidelines.

Figure 3.7 – Water pH reading using multi-parameter water quality device

Onsite tail water chemistry monitoring is required to ensure compliance with the environmental requirements and to meet tail water quality objectives that safeguard the ecologically sensitive North Queensland marine environment. In case the tail water pH is found to be outside the recommended threshold, pH reduction measures such water aeration with carbon dioxide are to be applied. Water aeration with carbon dioxide is a practical method that reduces tail water pH without adversely affecting other water quality parameters.

3.4 Results and discussion

Soft dredged mud slurry that was extracted from the Port of Townsville was stabilised with fly ash-based geopolymer binder. On land reclamation sites, a considerable waiting time is required for a newly-placed dredged mud slurry to settle and consolidate by its self-weight in order to gain sufficient strength to be traversed by ground improvement machinery. Alternatively, stabilising the dredged material while in slurry form reduces waiting time, saves costs and manipulates the engineering properties of the stabilised dredged mud prior to its formation. The study found, the fly ash-based geopolymer stabilised dredged mud slurries have bigger particles aggregation and have more flocculation settling, compared to the untreated dredged mud slurry. The flocculation is induced by electrochemical process of cation exchange. During the cation exchange process, identical charges are equally exchanged between seawater and dredged mud particles. Then, the flocculation settling regime is exacerbated by the fly ash-based geopolymer gel coating the mud particles in the dredged mud slurries. Thus, flocculation is found to be the main mechanism that governs the dredged mud slurry stabilisation with fly ash-based geopolymer binder.

The proposed soft dredged mud slurry stabilisation with fly ash-based geopolymer stabilisation has the advantage of no waiting time for reclaimed ground to be stiff enough to undertake the ground improvement. Compared to the other dredged material stabilisation methods such as chemical admixture, electrokinetic, surcharging, prefabricated vertical drain and stone columns, where reclaimed ground accessibility by construction plant and personnel is paramount. Other merits of the proposed dredged mud slurry stabilisation with fly ash-based geopolymer binder are, it is easily applicable on land reclamation with dredged mud slurry projects sites without the need to design or manufacture new equipment/plant. In addition, there is no need for developing new specific laboratory testing apparatus. This study was conducted using existing soil testing laboratory apparatus and concrete mixing equipment without or with minor modifications.

The geopolymer material is to be synthesised by a geopolymer batching plant (a modified concrete batching plant), where the dredged mud slurry mixing with the fly ash-based geopolymer binder is to be undertaken using a usual high-speed mixer. The geopolymer batching plant and the mixer are to be established on site near the dredged material pipeline, before the discharge point into land reclamation containment ponds. To enable direct mixing of dredged mud slurry with fly ash-based geopolymer binder, the dredged material pipeline and geopolymer batching plant are to be connected to the mixer. The mixer thoroughly mixes dredged mud slurry with the geopolymer binder and pump the fly ash-based geopolymer stabilised dredged mud slurry into the dredged material containment ponds. Schematic of onsite arrangement of dredged mud slurry stabilisation with fly ash-based geopolymer stabilisation is shown in Figure 3.9. For quality control, inspection and testing plans of the fly ash-based geopolymer synthesisation, geopolymer mix design proportion that are reported in geopolymer concrete literature are used. More testing is required to optimise the fly ash-based geopolymer material synthesisation mix design and the dredged mud slurry geopolymer stabilisation ratio.

Generally, any dredged material stabilisation method should stand on three legs: leg of cost effectiveness, leg of the stabilised dredged material performance and leg of environmental footprint. The dredged mud slurry stabilisation with the fly ash-based geopolymer binder can stand on all of these three legs. However, the exothermic and geopolymeric chemical reactions (equations 3.1 and 3.2) release free sodium ions (Na^+) into the tail water. The released sodium ions (Na^+) may adversely affect the tail water quality. Onsite tail water chemistry (pH) monitoring is required to ensure compliance with the environmental requirements and to meet tail water quality objectives.

Chapter 4: Sedimentation behaviour of fly ash-based geopolymer stabilised dredged mud

4.1 General

Sedimentation behaviour of soft soil slurry concerns civil and geotechnical engineers who deal with land reclamation with soft dredged mud slurries or mine tailings. The importance of understanding the sedimentation behaviour of soft soil particles comes from the close relationship between soft soil particles settling patterns and the geotechnical characteristics of the deposited final soft soil sediment. Ganesalingam et al. (2013) reported the settling behaviour of soil particles in a soil-water mixture would influence the homogeneity and consolidation properties of the final sediment. Compressibility and homogeneity characteristics of soft soil are important soil parameters for geotechnical application of land reclamation with soft dredged mud slurries.

The complexity of soft soil slurry sedimentation arises from view point that the soft soil particles settling behaviour is dependent on many factors (Tan et al. 1990). According to Imai (1980), the settling behaviour of clay suspension is controlled by two factors, degree of flocculation and degree of particles interaction. The degree of flocculation and the degree of particles interaction are influenced by the particle shape and size, particles concentration, mineralogy and suspension medium. The sedimentation process of clayey soil comprises three stages, no settling, but flocculation stage, flocs settling and soil sediment layer formation stage and self-weight consolidation stage (Imai 1981).

This laboratory experimental study has investigated the sedimentation behaviour of fly ash-based geopolymer stabilised soft dredged mud slurry that was extracted from eastern reclamation area at the Port of Townsville. Settling column tests were conducted to study the sedimentation behaviour of 400% water content dredged mud slurries of untreated and geopolymer stabilised at 6%, 12% and 18% by weight. During the settling column test, the untreated and the fly ash-based geopolymer stabilised dredged mud slurries settling patterns were observed, interface heights movements with elapsed time were recorded, settling curves and overall sedimentation duration were established.

4.2 Settling column experiment

As described by Trofs et al. (1996), settling and consolidation of soft soil particle are one-dimensional processes where sediments move downward; therefore, these processes can be simulated in laboratory by vertical settling column test. Settling column test is a simplified visual method for evaluating how soft soil particles settle in a water-soft soil mixture under gravity. Settling column test is widely used in civil and chemical engineering industries for its simplicity compared to the sophisticated mathematical models that describe the settling of soft soil suspensions processes. The objectives of the settling column experiment are:

- To visually observe the settling pattern and sedimentation stages of the untreated and the fly ash-based geopolymer stabilised dredged mud slurries;
- To record the dredged mud – clear water interface height variation with elapsed time;
- To measure the hydraulic retention duration of the untreated and the geopolymer stabilised dredged mud particles, and
- To measure the overall sedimentation duration of the untreated and fly ash-based geopolymer stabilised dredged mud slurries.

Jaditager and Sivakugan (2017) have advised the settling column test has limitation of settling tube wall hindering the horizontal movement of mud particles compared to mud particles movement in realistic land reclamation containment ponds or water treatment plant. However, there is agreement among the researchers, bigger settling column diameter generates better simulation, although, there no agreement on a recommended minimum settling column diameter. There is less concern about the sufficient material height that would safely simulate reality due to the assumption that is upon aggregation/ gaining enough weight, mud particles with similar sizes settle by gravity at approximately similar rate for different water column heights.

4.2.1 Preparation of untreated and fly ash-based geopolymer stabilised dredged mud slurries

The Port of Townsville's dredged mud was reconstituted in sea water that was taken from the Port of Townsville to form dredged mud slurry of 400% water content. The dredged mud slurries are prepared at 400% water content to simulate the actual dredged mud slurry that is generated by trailing hopper suction or cutter suction dredges on dredging and land reclamation sites. The Port of Townsville sea water has salinity of % 36.21 ppt (parts per thousand) and pH (Power of Hydrogen) of 8.0. The Port of Townsville dredged mud slurry was stabilised with fly ash-based geopolymer at 6%. 12 % and 18 % by weight as discussed in chapter 3, section 3.4.2 of this dissertation. The untreated and the fly ash-based geopolymer stabilised dredged slurries were thoroughly mixed to ensure the homogeneity of the fly ash-based geopolymer stabilised dredged mud mixture. Then, the untreated and the fly ash-based geopolymer stabilised dredged mud slurries were poured into four identical gradated cylindrical glasses that are shown on Figure 4.1.

4.2.2 Settling column experiment program

The sedimentation behaviour of the untreated and the fly ash-based geopolymer stabilised dredged mud slurries were investigated in laboratory by carrying out self-weight settling column experiment, similar to that was described by He et al. (2016). The untreated and the fly ash-based geopolymer stabilised dredged mud slurries were poured into four identical graduated glass cylinders that have 63 mm diameter by 500 mm high. While pouring the untreated and the geopolymer stabilised dredged mud slurries into the glass cylinders, same filling head and pouring rate was maintained for all cylinders. The graduated glass cylinders were filled with dredged mud slurry to height of 330 mm and the slurries were allowed to settle under their self-weight as shown on Figure 4.2. Adhesive paper tapes were attached to the outer walls of the glass cylinders to record the dredged mud-water mixture interface height movements with the elapsed time as specified by Guo et al. (2012). While undergoing sedimentation, the untreated and the fly ash-based geopolymer stabilised dredged mud slurries settling patterns were visually observed, clear water interface height movement with time were recorded. The dredged mud slurry sedimentation stage was assumed to be complete when the clear water – sediment interface height readings remained unchanged for more than three consecutive days (Jaditager and Sivakugan 2017).

Figure 4.1- From right to left settling column test of the untreated and the fly ash-based geopolymer stabilised dredged mud slurries at 6%, 12% and 18% respectively

4.3 Settling column test results

The results of the settling column test are presented in term of settling patterns, settling curves, and final sediment column heights in the following sections 4.3.1 to 4.3.3.

4.3.1 Settling patterns of the untreated and fly ash-based geopolymer stabilised dredged mud slurries

It was observed at the beginning of the self-weight settling column test the untreated dredged mud slurry took less time to form a visible soil-water mixture interface (i.e. shorter flocculation stage) in contrast to the other fly ash-based geopolymer stabilised dredged mud slurries. However, although it has shorter flocculation stage, the untreated dredged mud slurry has longer particles hydraulic retention time, and longer overall sedimentation duration compared to the fly ash-based geopolymer stabilised slurries. The time required by the fly ash-based geopolymer stabilised dredged mud slurries to form interface height was directly proportional to the geopolymer stabilisation ratio. In other word, the fly ash-based geopolymer dredged mud slurries flocculation stage length is related to their stabilisation percentage. This observation can be attributed to fact that the fly ash-based geopolymer gel induced flocculation governs the dredged mud slurry sedimentation parameters of settling velocity and deposition rates that are proposed by Droppo and Ongley (1989). Similarly, Mirzababaei et al. (2009) found the aluminosilicate geopolymer gel coating the clay particles in the slurry takes time to bring them closer to each other to converge together forming flocs that are bigger in size, thus settle faster as explained by Kranck (1975). The settling column test showed the sedimentation behaviour that was exhibited by the untreated and the geopolymer stabilised slurries is in general agreement with flocculated clay-water mixture slurry sedimentation staging of: flocculation stage, settling stage and consolidation stage that are reported by Imai (1981).

4.3.2 Settling curves of untreated and fly ash-based geopolymer stabilised dredged mud slurries

Figure 4.2 shows the interface heights movement versus elapsed time plotted on arithmetical scale for the untreated and the fly ash-based geopolymer stabilised dredged mud slurries. The presented settling curves summarise the sedimentation behaviours of the untreated and the fly ash-based geopolymer stabilised dredged mud slurries that are under investigation. In general, the settling curves of the untreated and the fly ash-based geopolymer stabilised dredged mud slurries have a similar shape. This is an indication that the untreated and the fly ash-based geopolymer stabilised dredged mud slurries settle in a similar manner, but at different selling rates. It is also observed, the untreated and the fly ash-based geopolymer stabilised dredged mud slurries have exhibited linear settling pattern at the beginning. Then, the linear settling pattern has followed by transitional zone of concave curves, and back to linear settling later on towards the end of the sedimentation stage. All the four settling curves have steep linear settling at the early settling stage, but flatter at the end of the sedimentation stage and the start of soil self-weight consolidation stage (effective stress existence). The settling curve for the untreated dredged mud slurry is characterised by shorter flocculation stage, longer settling stage which resulted into overall longer sedimentation duration. Where, the settling curves corresponding to the fly ash-based geopolymer stabilised dredged mud slurries showed longer flocculation stage, shorter settling stage with overall shorter sedimentation duration.

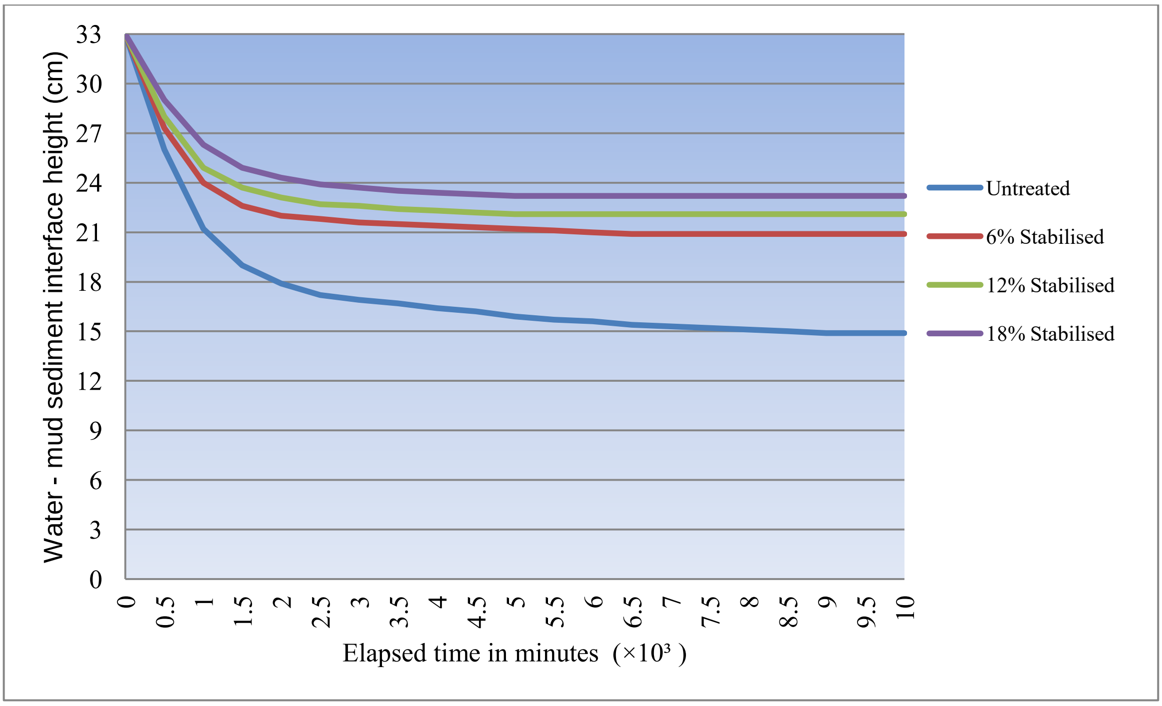


Figure 4.2 - Settling curves of untreated and fly ash-based geopolymer stabilised dredged mud slurries

4.3.3 Untreated and fly ash based geopolymer stabilised dredged mud sediment column heights

At the end of sedimentation stage, the height (i.e. the volume) of final dredged mud sediment column that was formed by the sedimentation process is found to increase with the increase of the fly ash-based geopolymer stabilisation ratio as shown in Figure 4.3. For the differences of the final soil column heights of the four dredged mud sediments, the results of this experimental study are comparable to Mitchell (1956) findings. Mitchell (1956) has suggested, for a given clayey soil mass, more flocculated soil fabrics occupies bigger volume compared to less flocculation or dispersed soil fabrics. For instance, Salehi (2009) reported clay soil fabrics that yield from flocculated sedimentation pattern occupy more volume than those formed by dispersed sedimentation process for the fact that, the flocculated clay particles associate edge - to –face to from card house soil structure. Also, this observation supports the hypothesis of soil fabric formed by flocculated settling occupies larger volume that was proposed by Ganesalingam et al. (2013).

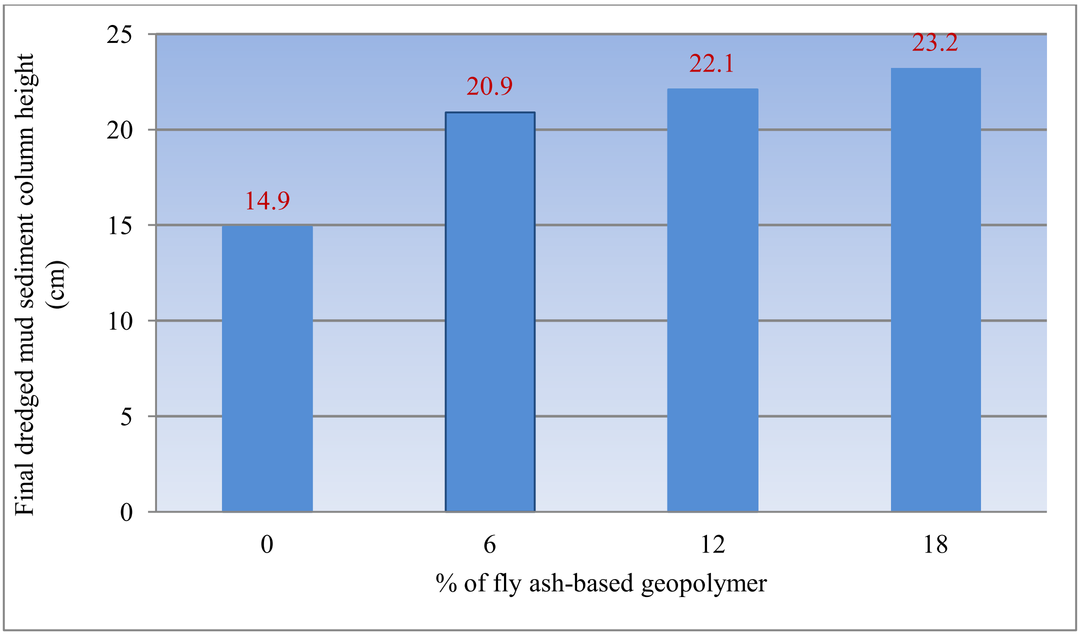


Figure 4.3 - Untreated and fly ash-based geopolymer stabilised dredged mud sediment final column heights

4.4 Discussion

The Port of Townsville soft dredged mud slurry was stabilised with the fly ash-based geopolymer binder. The influence of the fly ash-based geopolymer stabilisation on the sedimentation behaviour of the stabilised dredged mud slurry was examined by conducting settling column test. The study found the fly ash-based geopolymer gel coating dredged mud particles in the slurry has exacerbated flocculated settling behaviour and the geopolymer stabilisation has reduced the overall dredged mud slurry sedimentation duration. Also, the study found the fly ash-based geopolymer stabilisation has increased the volume of final stabilised dredged mud sediment that was formed by sedimentation and self-weight consolidation stabilised dredged mud slurry.

The conclusions of the settling column test are as follows:

- The flocculation that was exacerbated by the fly ash-based geopolymer gel coating the mud particles in the dredged mud slurry is believed to be the main mechanism that governs the dredged mud slurry sedimentation behaviour.
- Both untreated and the fly ash-based geopolymer stabilised dredged mud slurries have exhibited flocculated sedimentation behaviour, with flocculation increasing with the increase of fly ash-based geopolymer stabilisation percentage.
- The fly ash-based geopolymer stabilisation has reduced the overall dredged mud slurry sedimentation duration and increased the final sediment column height (volume).

Undesired land reclamation fill material properties, longer sedimentation duration, tail water stagnation and the associated generation of odour are among the geotechnical and environmental challenges port authorities and other land reclamation stakeholders have to manage. This study proposes fly ash-based geopolymer as alternative binder for soft dredged mud slurry stabilisation to: manipulate fill material formation, to reduce overall sedimentation duration and mitigate the tail water management issues. The findings of the study are applicable to in-situ dredged mud slurry on land reclamation by dredged mud slurry project site. The main variation between the sedimentation process of remoulded dredged mud slurry in laboratory and in-situ slurry on land reclamation site, is fill material segregation. The fill material segregation that occurs due to dredged mud slurry discharge outflow carries finer dredged mud particles away to the flow direction side of the containment ponds. However, on land reclamation with soft dredged mud slurry project sites, this variation is managed by rotating the dredged mud slurry discharge point to opposite sides of the containment ponds to redistribute the finer dredged mud particles by opposite direction discharge flow act.

The fly ash-based geopolymer stabilisation has induced bigger stabilised dredged mud sediment volume which requires larger containment ponds. This is a double-edged sword; the favourable consequence is gaining more fill material. The down side is, the bigger containment ponds require more capital expenditure (higher upfront funding model) to construct in shorter time frame, knowing, most of land reclamation works are long term projects with incremental funding strategies.

The practical implication of this laboratory experiment study findings on land reclamation with soft dredged mud project site are: expedited sedimentation that leads to less tail water management, quicker commencement of self-weight consolidation process that yields stiffer reclaimed ground and earlier utilization of the reclaimed land. Land reclaimed with soft dredged mud slurry takes time to settle, self-weight consolidate and gain sufficient strength to be trafficable for ground improvement plant. For the higher final sediment column (bigger volume) that is characterised the fly ash-based geopolymer stabilised dredged mud sediments dictates provision of bigger dredged mud containment ponds that have bigger capacity to accommodate the increased dredged mud sediment volume.

Chapter 5: Mineralogy and microstructure of untreated and fly ash-based geopolymer stabilised dredged mud

5.1 General

The use of advanced quantitative mineralogical and microstructural characterisation techniques has helped civil and geotechnical engineers to better understanding and correlating soft soil mineralogy and microstructure to its geotechnical parameters. Detailed mineralogical and microstructural analysis also provides reliable assessment of effectiveness of soft soil stabilisation methods and enables comparison between different stabilisation techniques and stabilisation percentages. According to Grubb et al. (2010), the assessment of mineralogical evolution of stabilised dredged material using X-ray diffraction with quantification analysis allow direct quantitative mineralogical comparisons between the stabilised dredged material. However, comprehensive characterisation of stabilised soft soil can be achieved by integrating geotechnical investigations (field and laboratory tests) with advance mineralogical and microstructural analysis.

The importance of knowing the mineralogy and microstructure of stabilised soft soil in geotechnical context comes from the close relationship between soil mineralogy and its mechanical properties. Soil mineralogy influences important soil chemical and physical properties such as cation exchange capacity and surface area (Hubert et al. 2009). According to Saussaye et al (2017), the mineralogy and microstructure of stabilised dredged marine sediment influences its compaction parameters, unconfined compressive strength, elastic modulus and its mechanical properties. As reported by Bellato et al (2013), microstructural and mineralogical evaluation of stabilised clay soil verifies the effectiveness of the soft soil stabilisation process and explains the underlying stabilisation mechanisms.

X-ray diffraction (XRD) is normally employed for phase identification of crystalline minerals and analysis of the effectiveness of soil stabilisation by comparing mineral concentration graphs that are obtained for the untreated and stabilised soils. Where scanning electron microscopy (SEM) with energy dispersive spectroscopy (EDS) analysis provide an insight into the achieved degree of stabilisation by investigating small areas of the soil specimen surface topography and chemical composition of the areas under examination.

5.2 Mineralogy of untreated and fly ash-based geopolymer stabilised dredged mud

To investigate the potential mineral alterations that may occur to the dredged mud sediments due to the fly ash-based geopolymer binder stabilisation, the mineralogy of untreated and the fly ash-based geopolymer stabilised dredged mud sediments were examined. Mineralogical characteristics of dried untreated and fly ash-based geopolymer stabilised dredged mud sediments were determined using X-ray diffraction (XRD) technique. Semi-quantitative X-ray diffraction analysis was performed on the Port of Townsville's dredged mud to determine its mineralogy by evaluating its mineral phase concentration. Cobalt radiation was used as source of radiation, and the mineral concentrations are calculated using the peak area integration method. The peak integration technique is a mineral concentration calculation method that considers the area under a powder XRD curve is function of diffraction intensity. The 100% peak for each mineral phase is summed and the relative percentages of each phase calculated based on the relative contribution to the sum.

5.2.1 Preparation of untreated and fly ash-based geopolymer stabilised dredged mud specimens for x-ray diffraction analysis

Representative dry untreated and fly ash-based geopolymer stabilised dredged sediment samples were prepared and lightly grinded in such a way that 90% was passing 20 µm. The grinding to this size helps eliminate preferred orientation. Then the prepared samples were placed into X-ray diffractometer samples holder ready for semi- quantitative X-ray diffraction analysis.

5.2.2 X-ray diffraction analysis

X-ray diffraction is widely used in soil mineralogy studies as it provides an accurate identification of mineral phase of the soil under investigation. X-ray diffractometer investigates the mineralogy of the soil under examination by scattering x-ray interaction with the electrons of the atoms in the soil material. For this experimental study, a Philips X'Pert automated powder diffractmeter in theta ($^{\theta}$) 2 theta ($^{\theta}$) geometry that deploys cobalt Kα radiation X-ray diffraction (XRD) system was used (Jaditager and Sivakugan 2017). Patterns were acquired over the range of 5° 2θ to 90° 2θ with a step size of 0.025°. The patterns are analysed by DIFFRAC.EVA phase analysis software version 3.1 with the International Centre for Diffraction Data (ICDD) 2014 database.

Only crystalline present in the dried untreated and the fly ash-based stabilised dredged mud sediment samples will give peaks in the X-ray diffraction XRD scan. The non-crystalline amorphous material in the dredged mud samples was added to the background. The mineral phase concentrations were calculated using peak area integration method.. The advantage of the peak area integration method is, it allows for some attention to be paid to the preferred orientation, however, it is limited in considering substitution and lattice strain.

5.2.3 X-ray diffraction analysis results

The results of the X-ray diffraction analysis of the untreated and the fly ash-based geopolymer stabilised dredged mud sediments are presented in term of their mineral components percentage by weight and the corresponding mineral phase concentration graphs. Tables 5.1 to 5.5 and Figure 5.1 to 5.4 show the mineral composition and the mineral phase concentration graph of the untreated and the fly ash-based geopolymer stabilised dredged mud sediments.

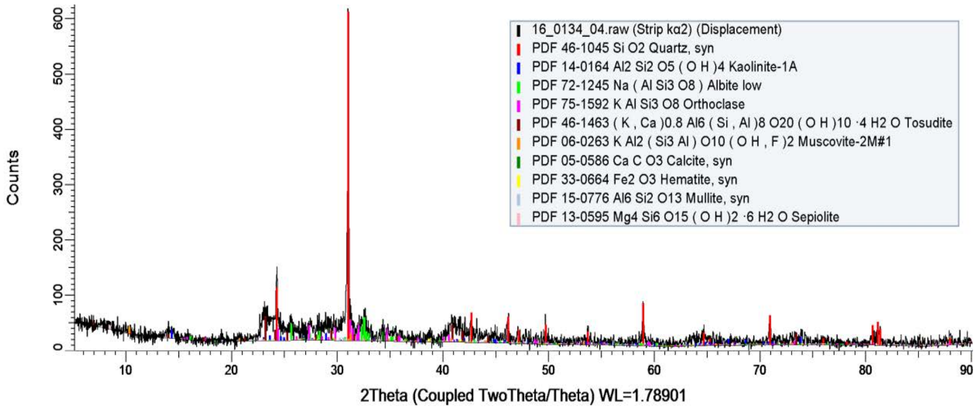


Figure 5.1 – X-ray diffraction patterns of the Port of Townsville untreated dredged mud

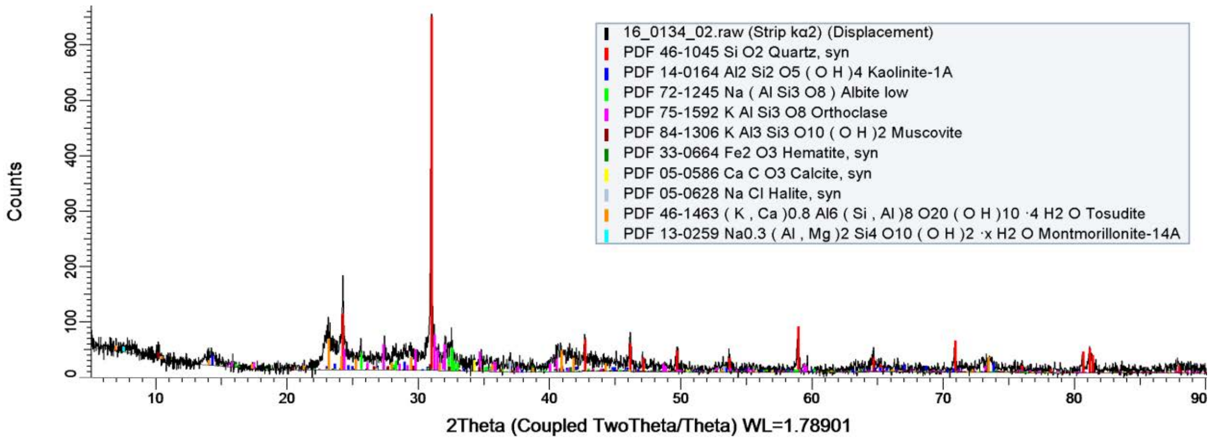


Figure 5.2 – X-ray diffraction patterns of the 6% fly ash-based geopolymer stabilised dredged mud

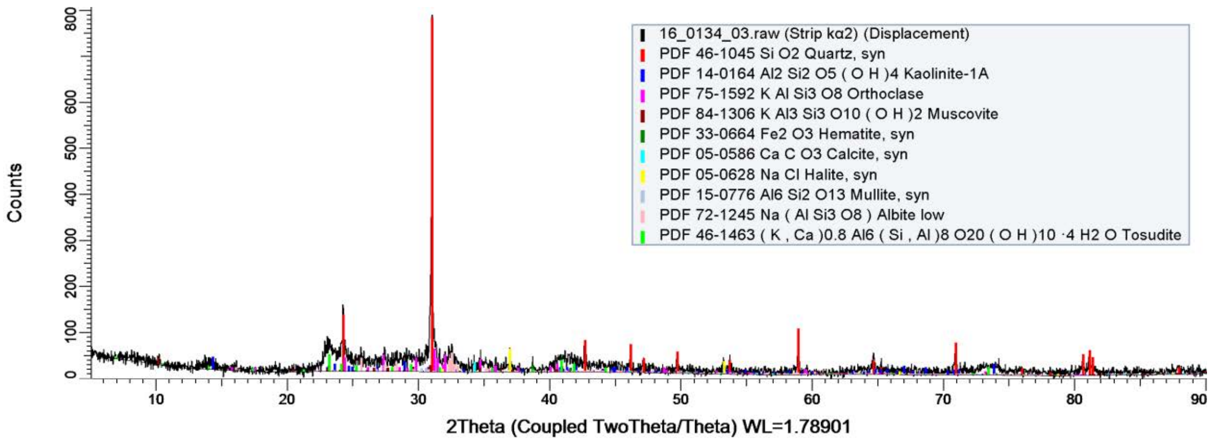


Figure 5.3 – X-ray diffraction patterns of the 12% fly ash-based geopolymer stabilised dredged mud

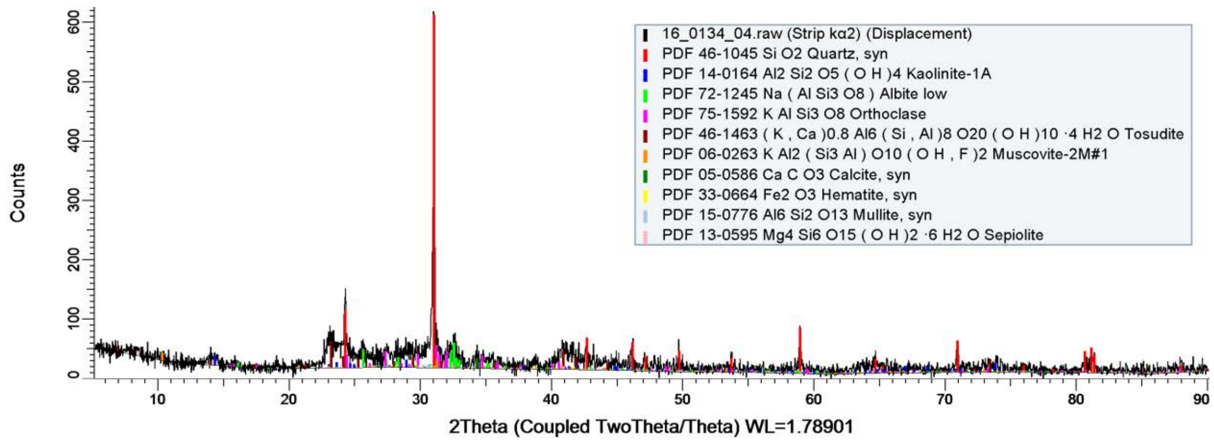


Figure 5.4 – X-ray diffraction patterns of the 18% fly ash-based geopolymer stabilised dredged mud

Table 5.1 Mineral compound of untreated and fly ash-based geopolymer stabilised dredged mud - summary

		Stabilisation % by weight			
Mineral compound	**Chemical formula**	0%	6%	12%	18%
Quartz	$Si\ O_2$	44	40	46	46
Albite	$Na\ (Al\ Si_3\ O_8)$	15	14	13	17
Orthoclase	$K\ Al\ Si_3\ O_8$	15	17	13	13
Tosudite	$((K,Ca)_{0.8}\ Al_6\ (Si,Al)_8O_{20}(OH)_{10}\cdot 4\ H_2O)$	12	12	8	12
Muscovite	$(K\ Al_3\ Si_3\ O_{10}\ (OH)_2)$	5	7	8	3
Kaolinite	$(Al_2\ Si_2\ O_5\ (OH)_4)$	4	4	6	4
Montmorillonite	$(Na_{0.3}(Al,Mg)_2Si_4O_{10}(OH)_2\ H_2O)$	2	2	2	2
Calcite	$(CaCO_3)$	2	2	2	2
Hematite	(Fe_2O_3)	1	1	1	1
Halite	$(NaCl)$	0	1	1	0

5.2.4 Discussion

The X-ray diffraction mineral composition analysis of the untreated and the fly ash-based geopolymer stabilised dredged mud sediments that are shown on tables 5.1 to 5.4 above are summarised in Table 5.5. As presented on mineralogy tables and the corresponding mineralogical phase concentration graphs, the untreated and the fly ash-based geopolymer stabilised dredged mud sediments contains almost the same mineral composition percentages by weight. The detected minerals comprises quartz ($SiO_{2)}$, albite (Na (Al Si_3 O8)), orthoclase (K Al Si_3O_8), tosudite ((K, Ca) $_{0.8}$ Al_6 (Si, Al $)_8$ O_{20} (OH $)_{10}$ $._4$ H_2O) and small percentages of muscovite , kaolinite, montmorillonite, calcite and hematite clay phases.

By comparing the -mineral phase composition of the untreated and the fly ash-based geopolymer stabilised dredged mud sediments that are shown in Table 5.5, it is clear that there are no notable variations between the untreated and the geopolymer stabilised dredged sediments in mineralogical terms. This is an indication, there is no fly ash-based geopolymer stabilisation induced new elements formation in the stabilised mud sediments. The lack of significant elemental differences between the untreated and the stabilised dredged mud sediments means there is no direct correlation between the fly ash-based geopolymer stabilisation and the mineralogy of the stabilised dredged mud sediment. This is a confirmation that the fly ash-based geopolymer gel is coating dredged mud particles in the dredged mud slurry is the main mechanism that governs the dredged mud slurry stabilisation with the fly ash-based geopolymer binder.

5.3 Microstructure of the untreated and the fly ash-based geopolymer stabilised dredged mud

Compressibility characteristics of a clayey soil are influenced by its microstructure. Tanaka and Locat (1999) have reported the microstructural framework of marine sediment influences its geotechnical behaviour. The pore space arrangement in the marine sediment has an impact on its compressibility and index properties such plastic and liquid limits. According to Terzaghi’s one-dimensional consolidation theory, any volumetric change in a saturated soft soil layer is attributed to pore water pressure dissipation process that caused by pore water expelled from pore space. To determine the potential changes that would occur to the stabilised dredged mud sediment due to the fly ash-based geopolymer stabilisation, the microstructure of the untreated and the fly ash-based geopolymer stabilised dredged mud sediments were examined. Micro-structural characteristics of the dried untreated and the fly ash-based geopolymer stabilised dredged mud sediments were determined using scanning electron microscopy (SEM) with energy dispersive spectroscopy (EDS) analysis.

5.3.1 Preparation of untreated and fly ash-based geopolymer stabilised dredged mud samples for SEM with EDS analysis

Representative dried untreated and fly ash-based geopolymer stabilised dredged mud sediment samples were prepared in optically flat format to avoid samples surface unevenness that adversely bias the elemental concentration interpretation. According to Heath and Taylor (2015), X-rays such as Kα radiation emitted by carbon, nitrogen and oxygen atoms are strongly affected by the geometry of the sample. For samples with uneven surfaces, the direction of the emitted X-ray deviates from the ideal linear absorption path that is provided by samples with flat surface. The prepared dredged mud sediment samples were carbon coated and placed on the top of double sided carbon tab. The carbon coating is undertaken to prevent charging of the dredged mud sediment samples whilst they are being analysed by electron beam.

5.3.2 Scanning electron microscopy (SEM) with energy dispersive spectroscopy (EDS) analysis

Scanning electron microscope is a useful tool for study of soil microstructure over wide range of magnification. According to Collins (1983), the SEM provides an indication of broad soil characteristics and assists in the interpretation of investigation results. In this laboratory experimental study, SEM with EDS analysis technique was used to examine the microstructure of the dried untreated and the fly ash-based geopolymer stabilised dredged mud sediments. The microstructure of the dried untreated and the fly ash-based geopolymer stabilised dredged mud sediments were analysed to study the influence of the fly ash-based geopolymer stabilisation on the microstructure of the geopolymer stabilised dredged mud. A Carl Zeiss EVO50 scanning microscope that is fitted with an

Oxford INCA X-Max EDS technology was used to analyse the microstructure of the untreated and the fly ash-based geopolymer stabilised dredged mud sediments.

5.3.3 Scanning electron microscopy (SEM) with energy dispersive spectroscopy (EDS) analysis results

The microstructural analysis results that are observed for the untreated and the fly ash-based geopolymer stabilised dredged mud sediment specimens are presented below in terms of SEM images and the corresponding EDS spectrograms. The microstructures of the untreated and the fly ash-based geopolymer stabilised mud sediment at 6%, 12% and 18% are shown on the annotated SEM images that are magnified to 90 μm shown on Figure 5.5a, 5.5b, 5.5c and 5.5d respectively. Where, the corresponding EDS spectrograms for the untreated and the fly ash-based geopolymer stabilised dredged mud sediments are presented on figures 5.6 to 5.9 on section 5.3.3.2.

5.3.3.1 Scanning electron microscopy (SEM) images

The SEM image for the untreated dredged mud sediment sample on Figure 5.5a shows relatively regular, dense clay matrix consistent with clay morphology that was described by James et al. (2008). Platy shaped clay particles with scattered silt grains and desiccation shrinkage cracks characterise the microstructure of the untreated dredged mud sediment.

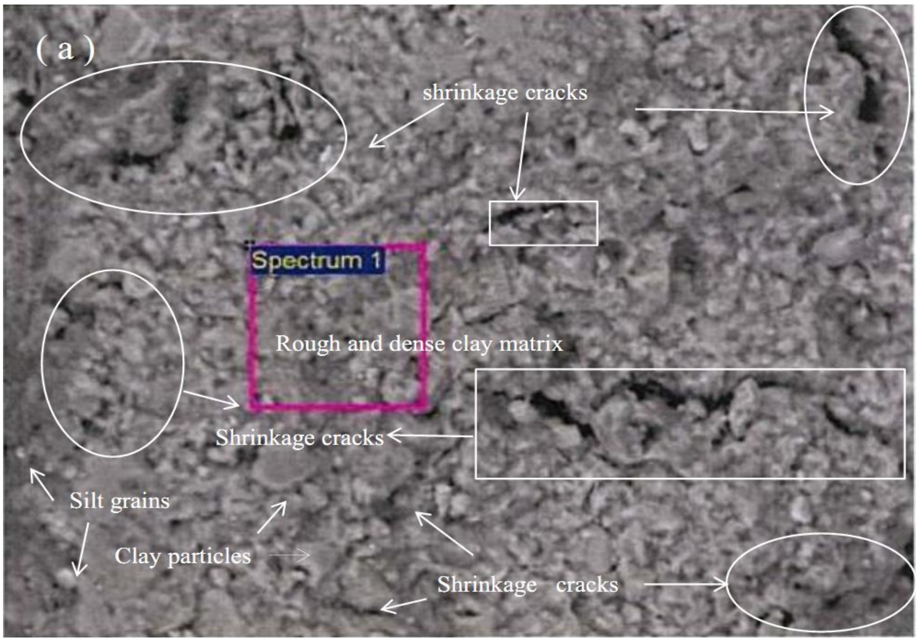


Figure 5.5a – SEM image of untreated dredged mud sediment

The SEM image shown in Figure 5.5b corresponds to the microstructure of 6% fly ash-based geopolymer stabilised dredged mud sediment. Figure 5.5b contained semi rough surface morphology that is featured by scattered silt grains, some un-reacted / partially dissolved fly ash spheres, coarse clay particle aggregation with few desiccation shrinkage cracks.

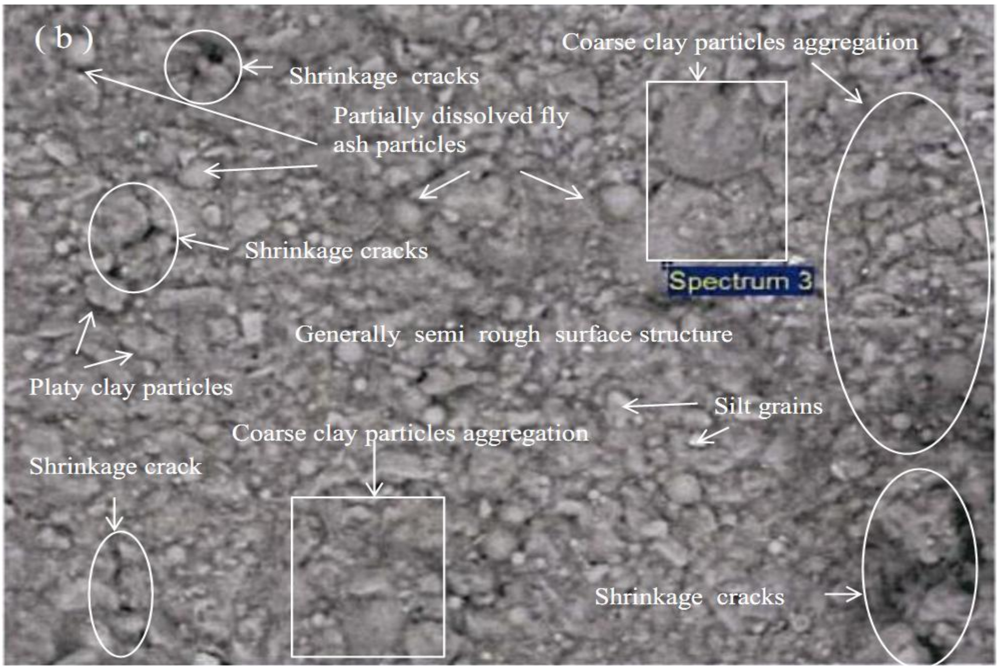


Figure 5.5b - SEM image of 6% fly ash-based geopolymer stabilised dredged mud sediment

Figure 5.5c, for the 12% fly ash-based geopolymer stabilised dredged mud sediment, exhibits a coarser microstructure and surface structure that is predominately featured to be rough, porous with hollow cavities and randomly oriented clay particle aggregations that are bigger in size. The fly ash-based geopolymer gel connector, undissolved/partially dissolved fly ash particles, scattered silt and clay particles are also apparent on the micrograph that is corresponding to 12% geopolymer stabilised dredged mud sediment.

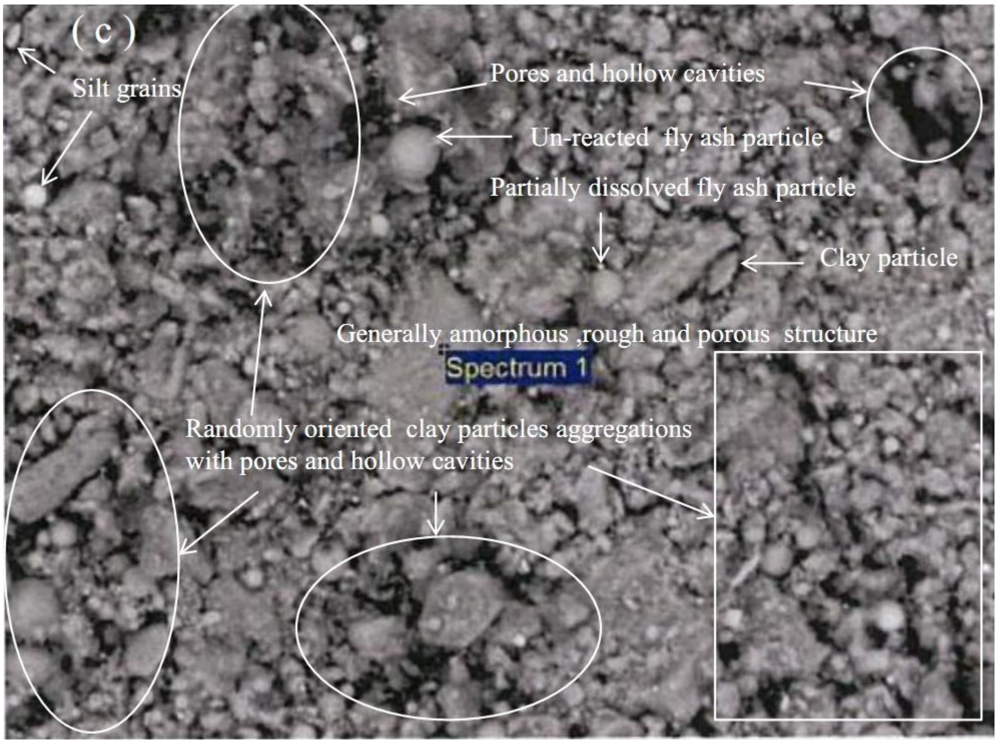


Figure 5.5c - SEM image of 12% fly as based geopolymer stabilised dredged mud sediment

The microstructure of 18% fly ash-based geopolymer stabilised dredged mud sediment Figure 5.5d is characterised by structured aggregated clay particles that are more uniformly connected by the fly ash-based geopolymer gel. The microstructure that is porous with hollow cavities and un-reacted / partially dissolved fly ash particles and some scattered silt grains are also noted on the surface of 18% fly ash-based geopolymer stabilised dredged mud sediment.

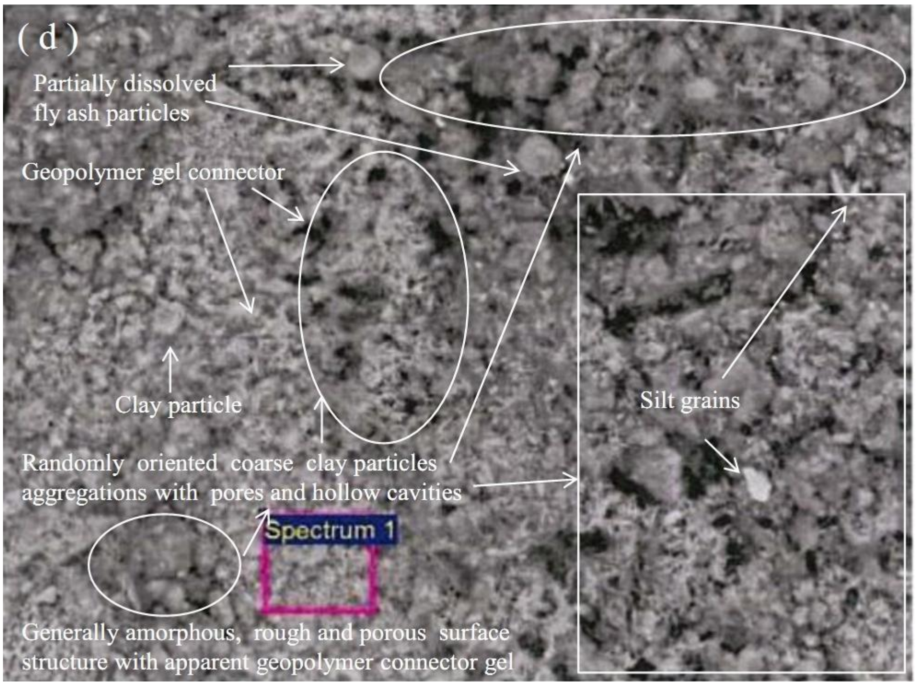
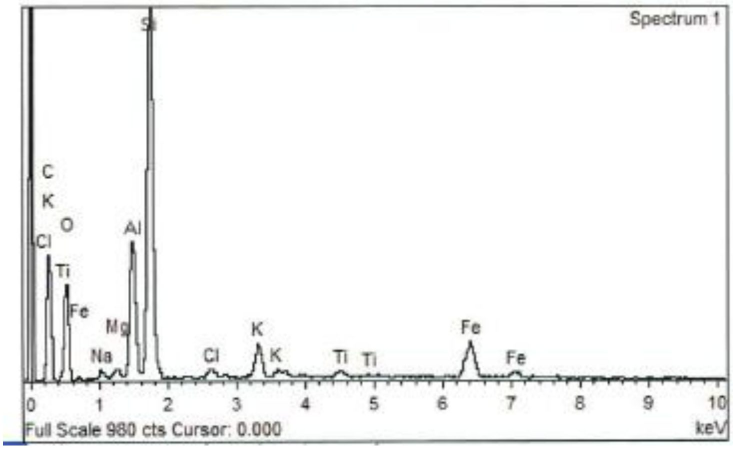


Figure 5.5d - SEM image of 18% fly ash-based geopolymer stabilised dredged mud sediment

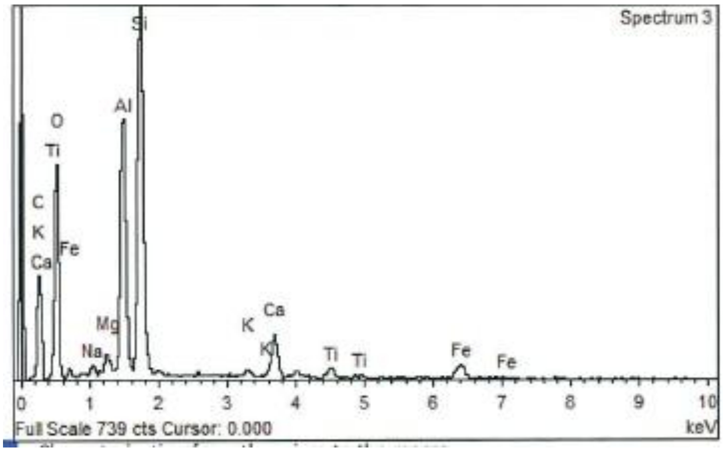
5.3.3.2 Energy dispersive spectroscopy (EDS) spectrograms

EDS spectrograms and inserted element percentage tables on Figures 5.6 to 5.9 show qualitative identifications of elements that are presents in spectrums surfaces of selected areas of SEM images for the untreated and the fly ash-based geopolymer stabilised dredged mud sediment specimens. The EDS spectrograms and the tables present the chemical composition of the dredged mud sediment in each spectrum area over the measurement of 10 points as described by Zhang et al. (2013).



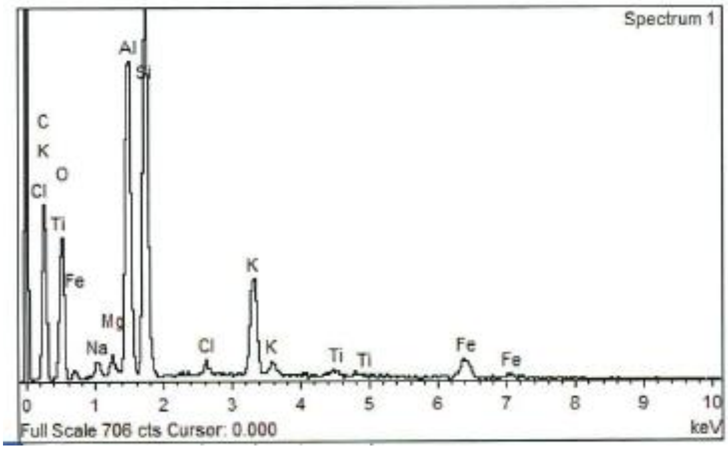
Element	Weight%	Atomic%
C K	48.22	63.01
O K	23.79	23.34
Na K	0.39	0.27
Mg K	0.29	0.18
Al K	4.56	2.65
Si K	13.84	7.73
Cl K	0.46	0.20
K K	1.81	0.73
Ti K	0.48	0.16
Fe K	6.16	1.73
Totals	100.00	

Figure 5.6 - EDS spectrogram and element percentage table for of untreated dredged mud sediment specimen



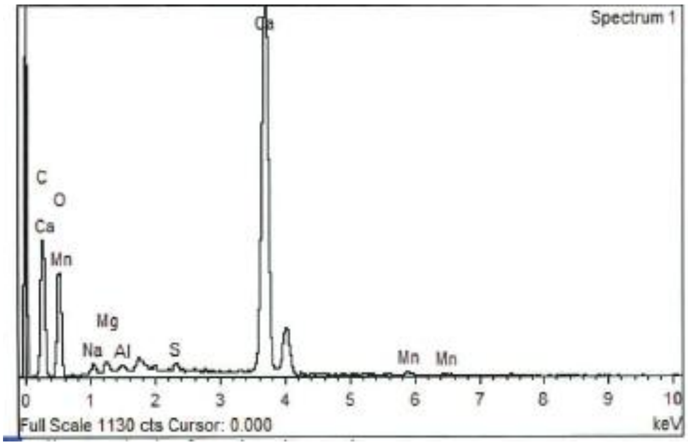
Element	Weight%	Atomic%
C K	35.26	47.27
O K	38.09	38.33
Na K	0.39	0.27
Mg K	0.56	0.37
Al K	7.76	4.63
Si K	12.78	7.32
K K	0.30	0.13
Ca K	2.11	0.85
Ti K	0.74	0.25
Fe K	2.01	0.58
Totals	100.00	

Figure 5.7 - EDS spectrogram and element percentage table for the 6% fly ash-based geopolymer stabilised dredged mud sediment specimen



Element	Weight%	Atomic%
C K	46.38	60.19
O K	26.92	26.23
Na K	0.63	0.43
Mg K	0.41	0.26
Al K	7.49	4.33
Si K	10.45	5.80
Cl K	0.44	0.19
K K	4.41	1.76
Ti K	0.34	0.11
Fe K	2.54	0.71
Totals	100.00	

Figure 5.8 - EDS spectrogram and element percentage table for the 12% fly ash-based geopolymer stabilised dredged mud sediment specimen



Element	Weight%	Atomic%
C K	26.07	38.75
O K	41.66	46.47
Na K	0.65	0.50
Mg K	0.52	0.38
Al K	0.29	0.19
S K	0.37	0.20
Ca K	29.92	13.33
Mn K	0.53	0.17
Totals	100.00	

Figure 5.9 - EDS spectrogram and element percentage table for the 18% fly ash-based geopolymer stabilised dredged mud sediment specimen

5.3.4 Discussion

Scanning electron microscopy (SEM) image of the untreated dredged mud sediment on Figure 5.5a showed the sedimentation formed final dredged mud sediment tends to have uniform and rough surface structure with apparent clay and silt particles, and desiccation shrinkage induced cracks that was described by Jaditager and Sivakugan (2017). Figure 5.5a, the SEM image for the untreated dredged mud sediment is also characterised by dense clay surface. The observed shrinkage cracks have exhibited two distinctive patterns, short and narrow cracks or elongated and wider cracks. The short and narrow patterned cracks are believed to be initiated by surface stress effect at the sediment – air interface at the start of the sediment drying. Whereas, the elongated wider patterned cracks were propagated later on by thermal stresses while the sediment was undergoing desiccation process as discussed by Miller et al. (1998). The laboratory observed elongated desiccation shrinkage cracks correlate well with field cracks that were noticed on the surface of the dredged material in the containment pond - the eastern reclamation area – the Port of Townsville as shown on Figure 5.10.

Figure 5.10 - Desiccation shrinkage cracks of dredged material in containment pond – eastern reclamation area- The Port of Townsville

Soil shrinkage cracks patterns shown for the Port of Townsville's reclaimed land fill material post its formation by sedimentation and self-weight consolidation of the dredged mud slurry are attributed to the moisture content variations that were caused by de-watering and solar drying processes. For the already consolidated and dry land reclamation fill material, dredged material shrinkage / swelling occurs due to the fill material moisture content fluctuation that was resulted from the tidal movement and seasonal rain fall. However, the shrinkage cracks and ground movement will adversely affect shallow foundations and pavement to be constructed on the reclaimed land. The fill material shrinkage is preferred to be reduced to minimize ground movement and maintain the structural integrity of the shallow foundations and pavement.

The surface structure of the 6% fly ash-based geopolymer stabilised dredged mud sediment shown on Figure5.5b has exhibited less desiccation shrinkage cracks, compared to the surface structure of the untreated dredged mud sediment on Figure 5.5a. Where, the surface structures of the 12% and the 18% fly ash-based geopolymer stabilised dredged mud sediments on SEM images Figure 5.5c and Figure 5.5d have shown no shrinkage cracks. A possible reason for this is, the fly ash-based geopolymer material possesses early strength, low shrinkage and thermal resistance properties that were reported by Wallah and Rangan (2006). The geopolymer literature shows the fly ash-based geopolymer material has advantage of low shrinkage. For example, Khater (2012) has proposed the water released during geopolymersation reaction resides within the cavities of the geopolymer structure mitigates shrinkage. Also, Azzam (2014) has concluded addition of polymer to clay soil forms nanocomposites materials that are considerably reduce the volumetric shrinkage strain. Geopolymer stabilised dredged mud sediment with improved shrinkage resistance reduces the risk of reclaimed ground shrinkage cracking that causes pavement and shallow foundation damages.

Scanning electron microscopy (SEM) images on Figures 5.5b, 5.5c and 5.5d showed the microstructures of the fly ash-based geopolymer stabilised dredged mud sediments at 6 %, 12% and 18 % respectively. It is observed, microstructures of the fly ash-based polymer stabilised dredged mud sediment are getting coarser with the increase of geopolymer stabilisation percentage. This coarse texture is attributed to increase in numbers and sizes of geopolymer gel coated / flocculated dredged mud particles that were reported by Jaditager and Sivakugan (2017). The numbers and sizes of geopolymer gel coated / flocculated mud particles increase with increase of geopolymer gel amount which drives flocs formation and aggregation in the fly ash-based geopolymer stabilised dredged mud slurry.

The settling pattern of soil particles during soft soil slurry sedimentation influences the association between particles of the formed final sediment fabric (Ganesalingam 2013). The microstructures of the fly ash-based geopolymer stabilised dredged mud sediments on Figure5.5b, Figure5.5c and Figure5.5d shown to be more amorphous and dominated by pores and hollow cavities with increase of the fly ash-based geopolymer stabilisation percentage. The existence of pores and hollow cavities can be owed to hollow cavities and porous nature that characterise the fly ash-based geopolymer material that was noticed by both Abdullah et al. (2012*)* and Skvara et al. (2005).

In contrast to the microstructure of untreated dredged mud sediment, the SEM image for the 6% fly ash-based geopolymer stabilised dredged mud sediment on Figure 5.5b shows generally semi-rough surface structure with some shrinkage cracks. Un-reacted and partially dissolved fly ash particles, coarse clay particles aggregation and scattered silt grains are also present on the surface of the 6% fly ash-based geopolymer stabilised dredged mud sediment. For the un-reacted and partially dissolved fly ash spheres that are apparent on the SEM micrographs of the fly ash-based geopolymer stabilised dredged mud sediments, it is well documented in the fly ash-based geopolymer literature , full dissolution of the fly ash into alkali activator solution is not achievable. Adam (2009) has concluded un-reacted and partially dissolved fly ash spheres make up a significant proportion of the total volume of geopolymer binder and they are expected to act as strength enhancers. The un-reacted or partially dissolved fly spheres are most likely to act as wedges within the fly ash-based geopolymer stabilised dredged mud sediment fabric ameliorating its strength properties (Jaditager and Sivakugan 2017). According to Wang et al. (2011), the fly ash has superior compressive strength property in contrast to soft dredged mud sediment.

Figure 5.5c, the micrograph for the 12% fly ash-based geopolymer stabilised dredged mud sediment exhibits a coarser microstructure that is predominately featured to be rough, porous with hollow cavities and particles that are bigger in size. This is similar to He et al. (2016) finding of flocculated sedimentation causes faster settling rates, and final sediment with larger particles that are randomly oriented. The findings of this laboratory experimental study are in general agreement with Ganesalingam et al. (2013) observation that in flocculated settling, random soil particles orientation occurs, resulting in a card house structure with large voids. The structured aggregated coarser clay particles that characterised the microstructure of the fly ash-based geopolymer stabilised dredged mud sediments is believed to be due flocculation mechanism as reported by Azam (2012).

Figure 5.5c, the SEM image for the 12% fly ash-based geopolymer stabilised dredged mud sediment has a coarser surface structure compared to the untreated and the 6% fly ash-based geopolymer stabilised dredged mud sediments. The microstructure of the 12% geopolymer-stabilised dredged mud sediment exhibits a rough and porous surface with hollow cavities and larger clay particles aggregations. Geopolymer gel binder, un-dissolved and partially dissolved fly ash particles, as well as scattered silt and clay particles featured the microstructure of 12% geopolymer stabilised dredged mud sediment.

For Figure 5.5d, the SEM image corresponding to the 18% stabilised dredged mud sediment; it has microstructure that is generally amorphous with visible fly ash-based geopolymer gel binder. Randomly oriented coarse clay particle aggregations with pores and hollow cavities characterise the microstructure of the 18% stabilised dredged mud sediment. Scattered un-reacted and partially dissolved fly ash particles and silt grains are also found on the surface structure of the 18% geopolymer stabilised dredged mud sediment. It is noticed that the stabilised dredged mud sediments particle aggregation sizes, pore number and size are increased with the increase of fly ash-based geopolymer stabilisation percentage. Consistent with the fly ash-based geopolymer stabilised dredged mud slurry settling rate, the geopolymer gels connectors are more apparent on the surface 18 % stabilised dredged mud sediment on Figure 5.5d which means more binding of dredged mud particles.

The variations in the microstructure of the fly ash-based geopolymer stabilised dredged sediments are mainly owed to the flocculated sedimentation regime that is caused by fly ash-based geopolymer stabilisation. Jaditager and Sivakugan (2017) has described the fly ash-based geopolymer gel coating the mud particles in the geopolymer stabilised dredged mud slurry exacerbates a flocculated sedimentation pattern. Thus, the geopolymer gel coating increases the sizes of the coated dredged mud particles, bringing them closer to each other to form aggregates that settle faster forming stabilised dredged mud sediment with altered microstructure. In a flocculated sedimentation of a dilute clay soil water mixture, soil particles flocculate in flocs, then the flocs mutually interact to form aggregates that are bigger in size and settle faster than the individual particles (Imai 1980).

According to Seng and Tanaka (2012), the microstructure of remoulded very soft clay sediment is governed by flocculated inter-particles rearrangement. Ganesalingam (2013) has stated, for high-water content dredged mud slurry that is settling under flocculated sedimentation, mud particles tend to form edge-to-face interrelation-ship and random aggregates association. Whereas, in dispersed slurry settling regime, dredged mud particles freely rotate to attain an orientation.

The apparent pores and hollow cavities that are increasing with the increase of geopolymer stabilisation percentage are the empty spaces that were caused by the water evaporation during the geopolymerisation process. Fan (2014) has claimed 70% of the water released during exothermic and geopolymeric chemical reaction evaporates. The pores and hollow cavities that are noticed on the microstructure of fly ash-based geopolymer stabilised dredged mud sediments are also in agreement with Abdullah et al. (2012*)* and Skvara et al. (2005) remarks. Both Abdullah et al. (2012*)* and Skvara et al. (2005) have observed fly ash-based geopolymer material is characterised by pores and hollow cavities.

Energy dispersive spectroscopy EDS spectrograms and the corresponding element percentage tables on Figures 5.6 to Figure 5.9 show sodium (Na) element was detected in both untreated and fly ash-based geopolymer stabilised dredged mud sediments, but at different atomic percentages. The sodium (Na) element has found to have atomic percentage of 0.27 in the untreated and the 6% fly ash-based geopolymer stabilised dredged mud sediments. Where, (Na) atomic percentages of 0.43 and 0.5 were detected for the 12 % and the 18% fly ash-based geopolymer stabilised dredged mud sediments respectively. For the untreated and the 6% fly ash-based geopolymer stabilised dredged mud sediment, the existence (Na) element is mainly owed to the sea water that was used to reconstitute the dredged mud slurry. However, for the (Na) element that is detected in the geopolymer stabilised dredged mud sediments, it is resulting from both the reconstituting sea water and the (Na) released from the geopolymerisation process as shown on equation 3.2.

Silica/ Aluminium (Si/Al) ration is another important observation that is common between the untreated and the fly ash-based geopolymer stabilised dredged mud sediments. Si/Al ration of 2.9, 1.6, 1.3 and 1 were observed for the untreated and the fly ash-based geopolymer stabilised dredged mud sediments at 6 %, 12 % and 18% respectively. The higher ratio is an indication of the source of the silica/ alumina is the dredged mud sediment rather than the fly ash-based geopolymer material. Where, the lower Si /Al ratio are detected in the geopolymer gel in the stabilised dredged mud sediment. The lower Si /Al ratio, the higher the geopolymerisation degree, hence higher the dredged mud stabilisation percentage

5.4 Summary

The mineralogy and microstructure of the untreated and the fly ash-based geopolymer stabilised at 6%, 12% and 18% by weight were investigated using X-ray diffraction XRD and scanning electron microscopy SEM with energy dispersive spectroscopy EDS analysis. Table 5.5 presents the summary of the mineral compositions of the untreated and the fly ash-based geopolymer stabilised dredged mud sediment specimens. As shown on table 5.5, there are no significant differences between the minerals that are detected in the untreated and the fly ash-based geopolymer stabilised dredged mud sediments.

The microstructures of the untreated and the fly ash-based geopolymer stabilised dredged mud sediments are presented on the annotated SEM images on Figure5.5a to Figure5.5d and the corresponding EDS spectrograms on Figures 5.6 to 5.9. From the mineralogical and microstructural analysis results that are obtained for the untreated and the fly ash-based geopolymer stabilised dredged mud sediment specimens the following conclusions can be drawn:

- There is no notable chemical elemental difference between the untreated and the fly ash-based geopolymer stabilised dredged mud sediments. In other word, the fly ash-based geopolymer stabilisation has not altered the chemical composition of the stabilised dredged mud sediments. As such, there is no direct correlation between the fly ash-based geopolymer stabilisation and the mineralogy of the geopolymer stabilised dredged mud sediment was established. However, dredged mud particles in the slurry were found to be compatible with the fly ash-based geopolymer binder.
- SEM images have shown significant microstructural variances between the untreated and the fly ash-based geopolymer stabilised dredged mud sediments. This is a confirmation that the geopolymer stabilisation has altered the microstructure of stabilised dredged mud sediments resulting in rough and porous morphology with hollow cavities, larger particles aggregation and reduced desiccation shrinkage cracks.

- The microstructural changes on the stabilised dredged mud sediments are attributed to the dredged mud slurry flocculation that is exacerbated by geopolymer gels coating the dredged mud particles in the slurries during the sedimentation stage of the fly ash-based geopolymer stabilised dredged mud slurries.

Chapter 6: Consolidation behaviour of fly ash-based geopolymer stabilised dredged mud

6.1 General

The rate and amount of consolidation of a soft soil is a vital geotechnical design input for construction on soft soil in general and reclaimed ground in particular. According to Tong et al. (2012), for land reclaimed with soft soil such as dredged mud, the fill material settlement characteristics define foundation design and construction works sequencing. Since introduced by Terzaghi as an experimental support for his one-dimensional consolidation theory, the standard one-dimensional consolidation test is widely used in soil laboratory to predict soft soil compressibility and consolidation. Typically, one-dimensional consolidation (Oedometer) test is performed to determine the magnitude and rate of volume decrease of a laterally confined soft soil specimen undergoes when subjected to different vertical pressures (Reddy 2002). The prediction of soft soil compressibility and consolidation behaviour guides the design, construction and maintenance of infrastructure assets that are to be founded on the soft soil. The anticipated duration for primary consolidation settlement by reclaimed ground self-weight alone, without ground improvement means, is always a major constraint to the utilisation of reclaimed land and meeting development time lines.

In this experimental study, the feasibility of the fly ash-based geopolymer as alternative binder for stabilising soft dredged mud slurry is investigated. The suitability of the fly ash-based geopolymer binder as soft dredged mud stabiliser is conditional to its influence on the engineering properties of the stabilised dredged. To ascertain its feasibility, the influence of the fly ash-based geopolymer binder on the compressibility and consolidation properties of the fly ash-based geopolymer stabilised dredged mud sediment were investigated by undertaking series of one-dimensional (Oedometer) tests.

6.2 Preparation of dredged mud sediment specimens for Oedometer test

There are logistical difficulties in obtaining identical high-quality soil specimens that have known stress history and homogeneous properties for laboratory testing. For this laboratory study, the preparation of dredged mud sediment specimens for the Oedometer testing was guided by Sheeran and

Krizek (1971) method of obtaining fine grained cohesive soil samples from higher water content slurry. To obtain high quality soft soil specimens, Sheeran and Krizek (1971) conducted a series of soft soil slurry sedimentation and self-weight consolidation in test tubes.

The untreated and fly ash-based geopolymer stabilised dredged mud slurries were poured into settling tubes and allowed three to four weeks to settle and commence self-weight consolidation. At the completion of the sedimentation stage, the surplus clear water that is accumulated on top of the dredged mud sediment columns is siphoned out using a pipette. The dredged mud slurry sedimentation stage is assumed complete when the clear water – dredged mud sediment interface height remained unchanged for more than three consecutive days as specified by Jaditager and Sivakugan (2017). 100 mm diameter filter papers and porous top plates were placed on the top of dredged mud sediment columns to allow the squeezed water out through the porous cap plate, but not the dredged mud sediment particles.

Incremental light loads in order of 50 to 300 grams were placed on the top of the dredged mud sediment columns after five weeks from the completion of the sedimentation stage. The dredged mud sediments were allowed to undergo consolidation under each incremental load for 3 to 7 days. The dredged mud sediment columns were loaded to maximum load of 3200g (4 kPa) over seven weeks' period. At the end of the loading stage, the Perspex cylindrical tubes were laid down horizontally on their sides; the porous bottom cap is un-bottled from the cylindrical tube base plates and removed as shown in Figure 6.1. The dredged mud sediment columns were pushed from the top by pressing on the top caps. Subsequently, the dredged mud sediments protrude out through the bottom of the cylindrical tube (Figure 6.1). The bottom 50 mm of the dredged mud sediment columns were cut out to ensure homogenous and high-quality specimens are obtained (Jaditager and Sivakugan 2018). The Oedometer test specimens were extracted by pushing 76 mm diameter by 20 mm high Oedometer ring into the centre of the dredged mud sediment columns and gently pulling it out.

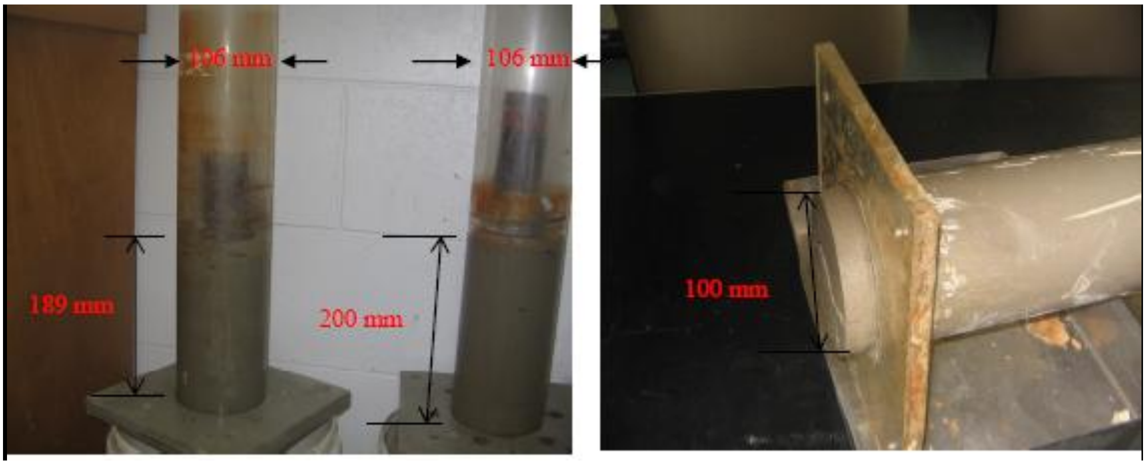


Figure 6.1 - Untreated and 6% fly ash-based geopolymer stabilised dredged mud sediments loading and Oedometer test specimen preparation

6.3 One dimensional consolidation test program

The influence of the fly ash-based geopolymer binder on the consolidation behaviour of the stabilised dredged mud sediment is of interest of this experimental study. Subsequently, compressibility and consolidation characteristics of the Port of Townsville's reconstituted dredged mud sediment that are untreated and fly ash-based geopolymer stabilised at 6%, 12% and 18% by weight were investigated in laboratory. A series of standard one-dimensional consolidation (Oedometer) tests were undertaken to assess the consolidation properties of the untreated and the fly ash-based geopolymer stabilised dredged mud specimens (Figure 6.2). Oedometer testings were conducted in accordance with Australian Standard (AS1289.6.6.1) methods of testing soils for engineering purposes – determination of one-dimensional consolidation properties of a soil. Adhering to the conditions of Terzaghi (1943) one-dimensional consolidation theory, the dredged mud specimens were kept saturated throughout the testing duration by topping up the water in specimens confining consolidation rings.

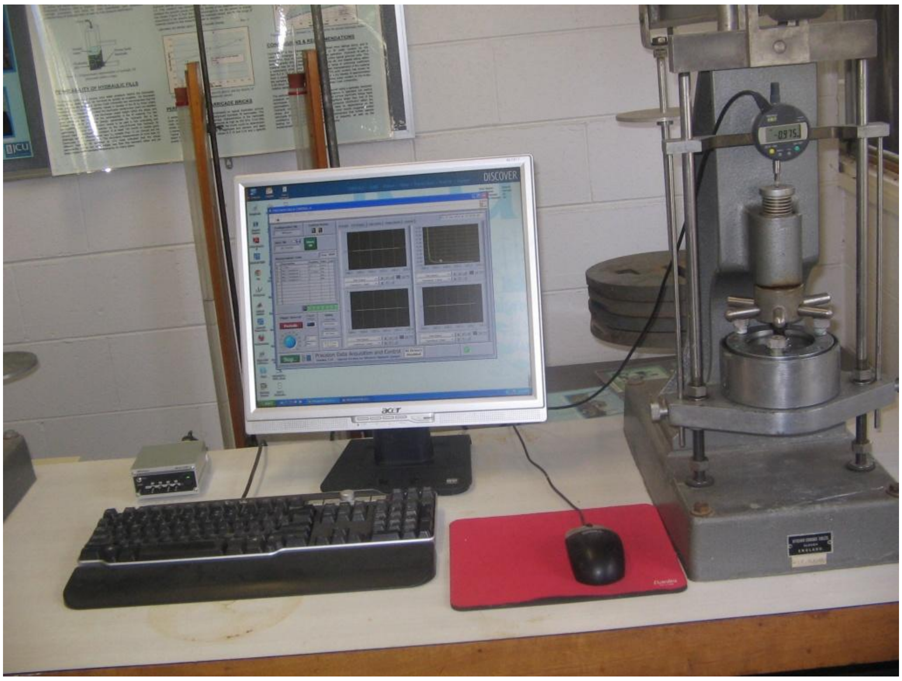


Figure 6.2 – Oedometer test set up with data logger

6.3.1 Loading of untreated and fly ash-based geopolymer stabilised dredged mud specimens

Yong and Townsend (1986) has described incremental loading consolidation test as the most conventional and common method of testing. The incremental loading consolidation test applies daily increment of vertical load to a submerged soil specimen that is contained in a rigid ring with double drainage permitted through the porous stones at the top and the bottom. The 76 mm in diameter by 20 mm high untreated and fly ash-based geopolymer stabilised dredged mud specimens were subjected to incremental vertical stresses of: 5 kPa, 10 kPa, 20 kPa, 40 kPa, 80 kPa and 160 kPa. During the consolidation test, each loading was kept for at least 24 hours before adding the next load increment to achieve 90% primary consolidation. As described by Feng et al. (2001) load increment ratio of 1 was chosen to ensure the dredged mud sediment specimens' consolidation curves are similar to Terazghi's theoretical consolidation curves.

6.3.2 Dredged mud sediment deformation versus time data logging method

During the dredged mud specimen's consolidation testing, the specimens' deformation versus time readings for each load increment was continuously captured using Mitutoya data logging system. The

Mitutoya digital deformation gauge is connected to the Oedometer as shown above on Figure 6.2. The Mitutoya digital deformation gauge continually transmits real-time dredged mud sediment deformation with the elapsed time data to the data logger that is connected to a computer. Precision data acquisition and control software version 7.21- LabVIEW program was used to acquire and process the dredged mud sediment settlement versus time data in text format. The logging interval for each specimen was set at every second for the first hour, and then every fifteen minutes thereafter. The captured laboratory data analysed and the deformation versus time information is used to plot consolidation curves.

The consolidation curve for the untreated and the fly ash-based stabilised dredged mud specimens' consolidation curves enable the estimation of their volume compressibility coefficient (m_v), void ratio (e), coefficient of consolidation (c_v), and permeability coefficient (k). These estimated geotechnical properties are used in prediction of the time rate and extent of settlement structures to be constructed on soft reclaimed ground would undergo. The compressibility and consolidation characteristics of the dredged material also assist in land reclamation fill material stress history analysis and comparison of ground improvement options.

6.3.3 Consolidation curves fitting method.

Using dredged mud sediment deformation versus time data that were obtained from one dimensional consolidation tests, the coefficient of consolidation (c_v) of the untreated and the fly ash-based geopolymer stabilised dredged mud sediments for each incremental loading were estimated. Lovisa (2012) has assessed the efficacy of some of the popular curve fitting methods that are used for estimating coefficient of consolidation (c_v) of soft soils and found Taylor's square root of time method yields the most accurate (c_v) values. Taylor (1942) square-root of time curve fitting method was uses to estimate the coefficient of consolidation (c_v) of the untreated and the fly ash-based geopolymer stabilised dredged mud sediments (Figure 6.3).

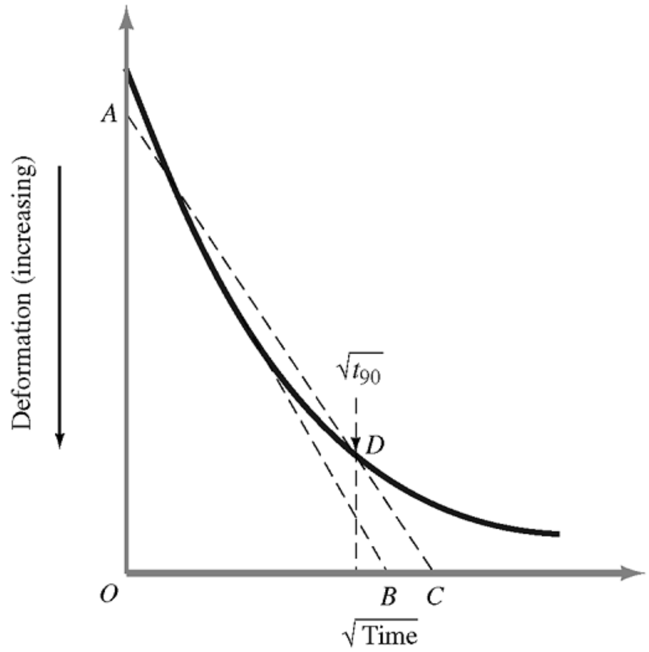


Fig 6.3 - Taylor square-root of time method (El Shenawy 2003)

On Figure 6.3, line *AB* represents the early portion of the consolidation curve, where line *AC* is drawn in such a way $OC = 1.15OB$. The abscissa of point *D*, the intersection of line *AC* and the consolidation curve gives the square root of time required to achieve 90% of primary consolidation of the soft soil under investigation.

6.3.4 One-dimensional consolidation test results

The untreated and the fly ash-based geopolymer stabilised dredged sediment specimens' deformation rate and amount that are anticipated to occur due to pressure increase at any given time is determined by compressibility, consolidation and permeability properties of the dredged material. The consolidation behaviour of the untreated and geopolymer stabilised dredged mud sediments were investigated by studying their volume compressibility coefficient (m_v), void ratio (e), coefficient of consolidation (c_v), and permeability coefficient (k). The one-dimensional consolidation test results are presented in basis of logarithm of pressure (log) scale as shown below on Figures 6.4 to 6.8. According to Wesley and Pender (2008), the origin of using the logarithm of pressure (log) plot in presenting the oedometer test results lies in the way in which sedimentary soils behave when initially consolidated.

6.3.4.1 Coefficient of volume compressibility (m_v) of untreated and fly ash-based geopolymer stabilised dredged mud sediment specimens

The compressibility of the untreated and fly ash-based geopolymer stabilised dredged mud sediments variation with geopolymer stabilisation percentage and the applied pressure are investigated using (m_v vs log) compression curves. The (m_v vs log) plot on Figure 6.4 shows, for similar loading conditions, the coefficient of volume compressibility (m_v) of dredged mud sediment decreases with the increase of fly ash-based geopolymer stabilisation percentage.

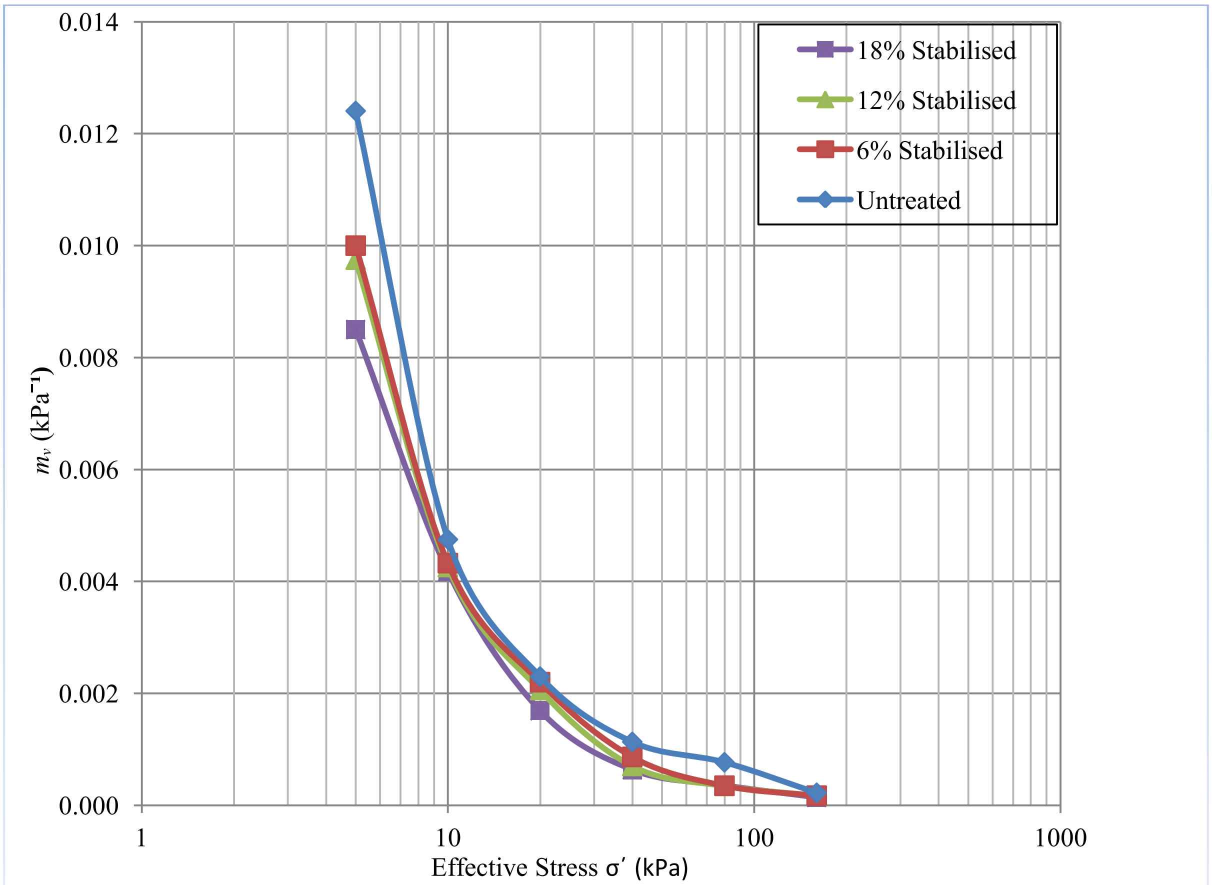


Figure 6.4 -Variation of volume compressibility coefficient (m_v) with effective stress ( ) and fly ash-based geopolymer stabilisation percentage

6.3.4.2 Void ratio (e) of untreated and fly ash-based geopolymer stabilised dredged mud sediments

The void ratio is among soil parameters that are needed to be considered when studying the consolidation behaviour of soft soil such as dredged mud sediment. The dredged mud sediment specimens void ratio (e) variations with the fly ash-based geopolymer stabilisation percentages and the applied effective stress ( ) is shown below on (e vs log) graph (Figure 6.5).

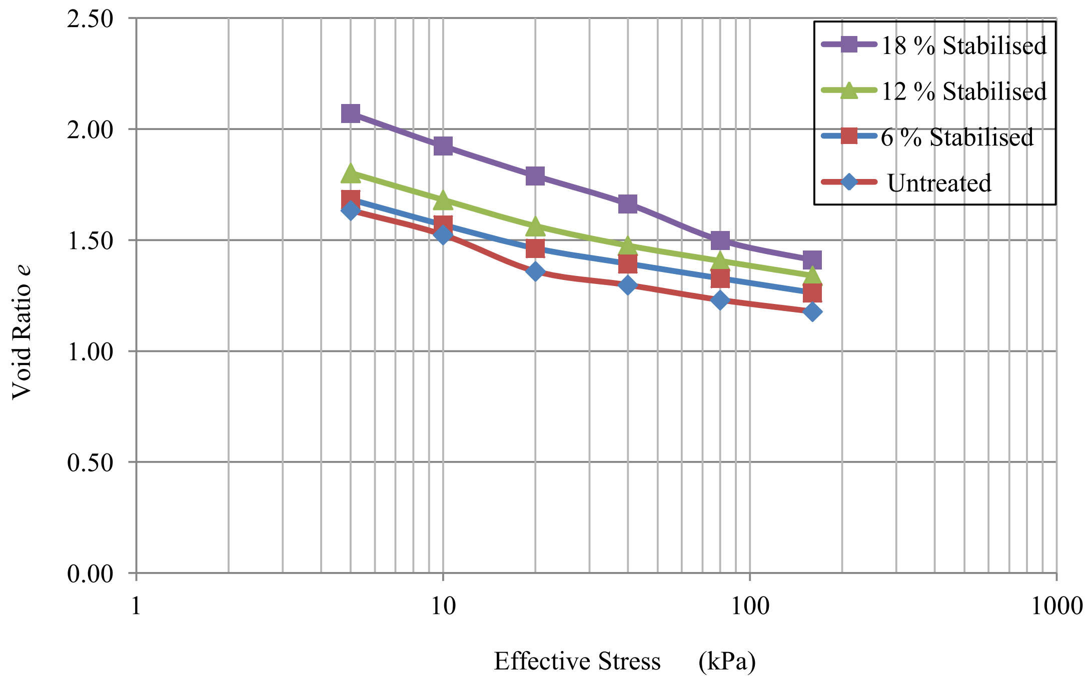


Figure 6.5 - Void ratio (e) variation with effective stress ( ) and the fly ash-based geopolymer stabilisation percentage

6.3.4.3 Coefficient of consolidation (c_v) of untreated and fly ash-based geopolymer stabilised dredged mud sediments

The coefficient of consolidations (c_v) of the untreated and the fly ash-based geopolymer stabilised dredged mud sediments that are subjected to a similar effective stress are illustrated by (c_v vs log) curves on Figure 6.6.

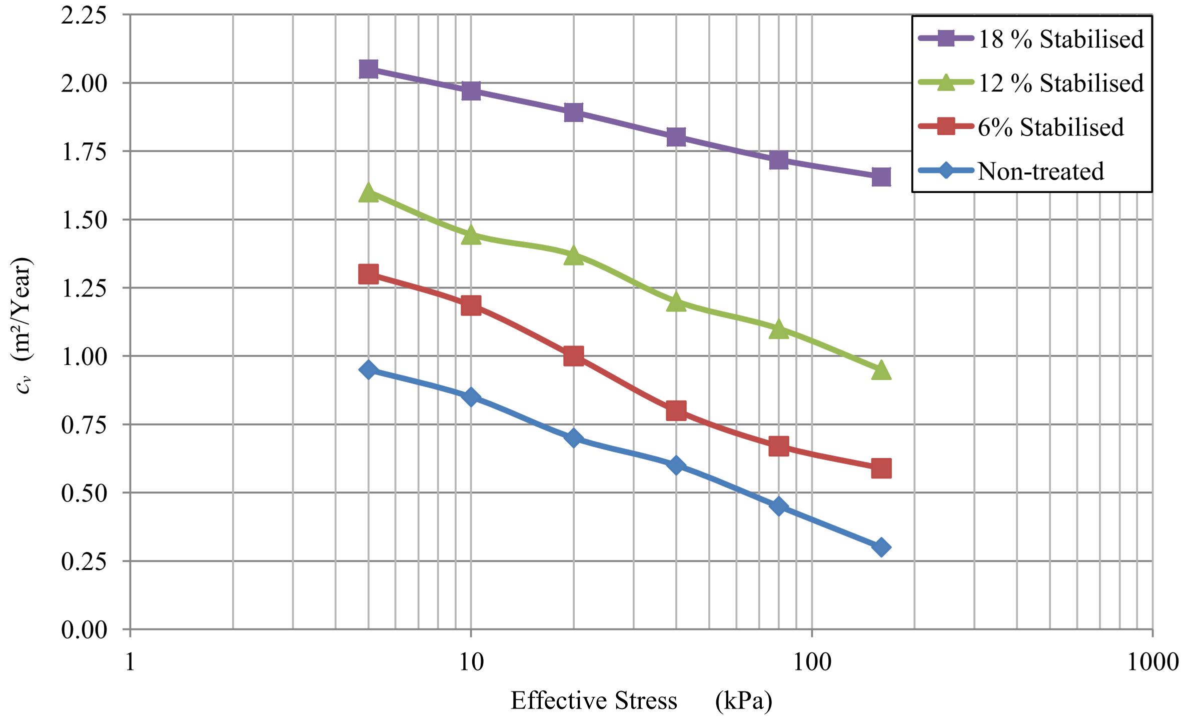


Figure 6.6 - Coefficient of consolidation (c_v) variations with effective stress( ) and the fly ash-based geopolymer stabilisation percentage

6.3.4.4 Permeability coefficient (k) of the untreated and fly ash-based geopolymer stabilised dredged mud sediments

The permeability coefficient (k) for the untreated and the fly ash-based geopolymer stabilised dredged mud sediments are analytically estimated based on the coefficient of consolidation (c_v) and the coefficient of volume compressibility (m_v) values. (k vs log) curves that are shown on Figure 6.7 outlines the variation of permeability coefficient (k) with effective stress ( ) and fly ash-based geopolymer stabilisation percentage.

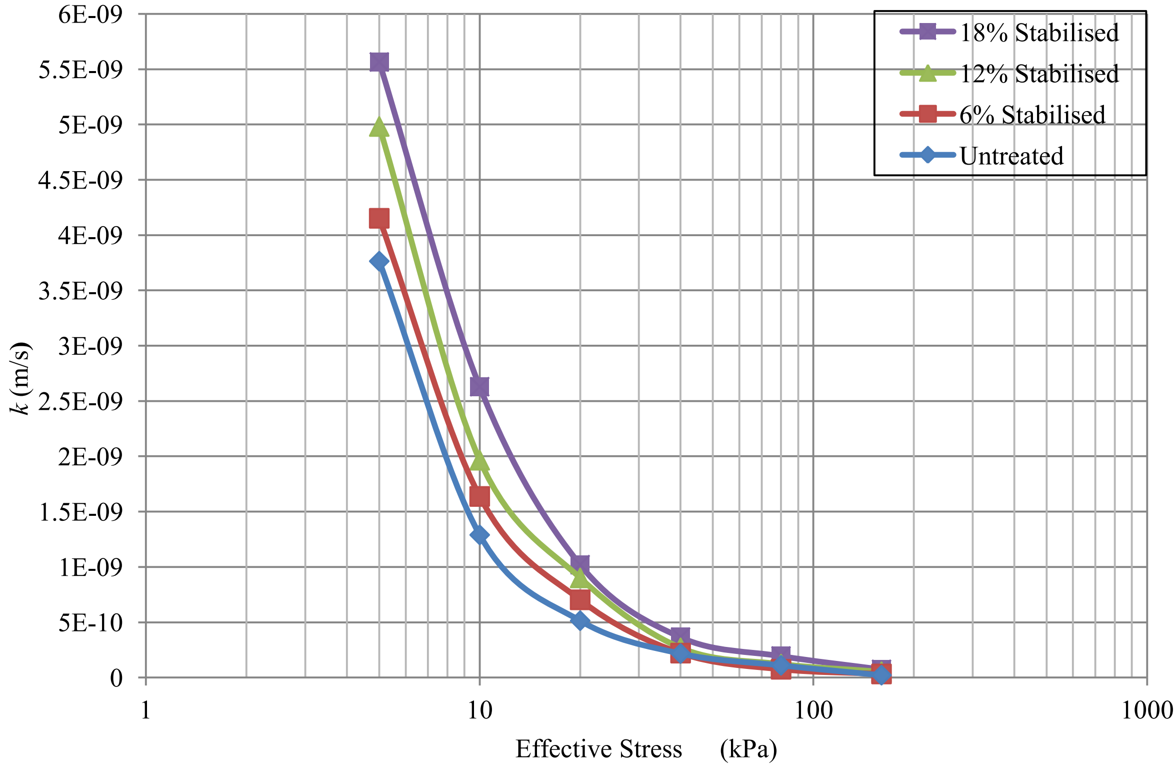


Figure 6.7- Variation of permeability coefficient (k) with effective stress ( ) and fly ash-based geopolymer stabilisation percentage

6.4 Coefficient of consolidation (c_v) of untreated dredged mud sediment - laboratory obtained versus field measured values

Jaditager et al. (2015b) noted back-calculated field (c_v) value for the fill material of eastern reclamation area - the Port of Townsville for applied effective ( ) of 40kPa was 4.0 m²/year. Compared to this study's laboratory estimated (c_v) value of 0.6 m²/year for the untreated dredged mud sediment, the field (c_v) is far greater. This can be attributed to in-situ fill material geotechnical properties and drainage conditions vary across the Port of Townsville's eastern land reclamation site. For example, the most seaward dredged material containment pond, from which the dredged mud samples that were used in this study are excavated, contains the softest dredged material. The fine grained dredged material in this particular seaward pond was carried by dredged mud slurry discharge flow through a network of containment ponds and weir boxes to settle just before the tail water discharge into the ocean. Presence of pebbles, sand pockets and sea shell debris in the in-situ compressible fill material also facilitate faster pore water dissipation process. Where, the laboratory tested reconstituted dredged mud sediment is sieved via 2.38 mm sieve mesh to remove pebbles and other larger particles.

Beside the in-situ geotechnical and drainage conditions variations, geotechnical engineers widely believe laboratory estimated (c_v) values are significantly less than back-calculated field (c_v) values. Sivakugan and Das (2010) have reported field consolidation takes place in faster rate than laboratory, and laboratory methods underestimate (c_v) values. Back calculated (c_v) values are more reliable than laboratory estimated values as Oedometer test neglects potential inclusion of sand and silt in the land reclamation fill material (Ganesalingam et al. 2011). According to Crawford (1986), the rate of soil consolidation in field is faster than the estimated based on laboratory tests; due to the resistance to deformation of the soil structure masks the hydrodynamic effect, leading to under estimation of the soil permeability. Lovisa (2012) has also reported that soils are more permeable in field, especially in the horizontal direction than the measured in unidirectional in the laboratory

To capture the ground variability within a reclaimed land due to geotechnical and drainage variability, geotechnical data that are considered giving the most probable consolidation are to be chosen for consolidation settlement calculations. Realistic evaluations of land reclamation fill material geotechnical parameters and geotechnical acumen are important factors to be taken in consideration while estimating consolidation rate and settlement amount of reclaimed land. Some adjustments to fill material geotechnical properties are also necessary to account for anomalies expected between laboratory measured and in-situ soil properties. Similarly, sub diving of the reclaim area into lots that are anticipated having similar geotechnical conditions and piecemeal geotechnical investigations mitigate these variations. Piecemeal basis geotechnical investigation is to provide a comprehensive soil characterisation of specific lots of reclaimed land when its intended use and reclaimed ground performance requirements are known.

6.5 Discussion

For the compressibility of the untreated and fly ash-based geopolymer stabilised dredged mud sediments specimens, the (m_v vs log) plot on Figure 6.4 outlines , for similar loading conditions, the coefficient of volume compressibility (m_v) of dredged mud sediment decreases with the increase of fly ash-based geopolymer stabilisation percentage. In other words, the fly ash-based geopolymer stabilisation increases the stiffness of the dredged mud sediment. For a given effective stress, the stiffness of dredged mud is dependent on its compressibility properties. For effective stress of 40kPa, (m_v) values of: 1.13×10^{-3} kPa^{-1}, 0.863×10^{-3} kPa^{-1}, 0.701×10^{-3} kPa^{-1} and 0.634×10^{-3} kPa^{-1} were estimated for dredged mud sediments of untreated, fly ash-based geopolymer stabilised at 6%, 12% and 18% respectively. The estimated (m_v) values indicate the fly ash-based geopolymer stabilisation has resulted into stabilised dredged mud sediment that is less compressible. The fly ash-based geopolymer stabilisation of dredged mud slurry causes a flocculated sedimentation regime which in turn alters microstructure of the resulting dredged mud sediment (Jaditager and Sivakugan 2017). The fly ash-based geopolymer stabilisation of high water content dredged mud slurry leads to geopolymer gel coating dredged mud particles causing particles aggregation and flocculated sedimentation pattern. As suggested by Sasanian and Newson (2014), clay soil aggregates or clusters are fundamental components that control strength and stiffness properties of the soil.

In the soft soil literature, researches that are conducted by Mitchell (1956), Locat and Lefebvre (1985), and Salehi (2009) suggested, flocculated sedimentation regime increases the compressibility of the resultant clay soil. However, Hogg (2000) has reported the microstructure of clay soil fabric that is formed by polymer induced flocculation sedimentation regime has lower compressibility. Also, Azzam (2014) has illustrated the added polymer molecules attach themselves to clay particles and construct nanocomposites within the inter-assembling voids of stabilised clay matrix. Then, the constructed nanocomposites act as filler material that decreases the compressibility and volumetric shrinkage of the polymer stabilised clay soil. In addition, the un-reacted and partially dissolved fly ash particles that are apparent on the microstructure of the geopolymer stabilised dredged mud sediments are expected to enhance stiffness and reduce compressibility. The fly ash particles have superior compressibility properties compared to dredged mud particles. Tu et al. (2007) have tested a class F fly ash that was collected from Cardinal power generation in Brilliant, Ohio USA and found its compressibility is comparable to that of inorganic silty sand and poorly graded sand. Phanikumar and Sharma (2007) reported stabilisation of highly plastic expansive soil with 20% fly ash has resulted to 40% reduction in compression index of the expansive clay.

Figure 6.5, (e vs log) graph shows the relationship between dredged mud sediments void ratio (e), applied effective stress ( ) and fly ash-based geopolymer stabilisation percentage. Consistent with the fly ash-based geopolymer stabilised dredged mud sediments microstructure observations, void ratio (e) of stabilised dredged mud sediment increases with the increase of geopolymer stabilisation percentage. The increased void ratio is due to geopolymer stabilised dredged mud slurries' flocculated sedimentation pattern that was caused by the fly ash-based geopolymer stabilisation. It is widely accepted among geotechnical researcher that flocculated sedimentation of soft clayey soil slurry results in clay particles arrangement with increased void ratio. Salehi (2009) has concluded flocculated dredged mud slurry sedimentation results in dredged mud sediment that has cards house structure and increased void ratio. Where, Haase and Shanz (2016) have recorded addition of polymer to clay soil forms clay-polymer composite microstructure with restriction in clay particles arrangement and increased void ratio.

Figure 6.6, (c_v vs log) curves compares coefficient of consolidation (c_v) of the untreated and the fly ash-based geopolymer stabilised dredged mud sediments that were subjected to a similar effective stress. As seen in Figure 6.6, (c_v) of a dredged mud sediment increases with the increase of fly ash-based geopolymer stabilisation percentage. At effective stress of 40 kPa, (c_v) value for the untreated dredged mud sediment is 0.6 m^2/year. For the same effective stress of 40 kPa, (c_v) values of: 0.8 m^2/year, 1.2 m^2/year, and 1.8 m^2/year were estimated for dredged mud sediments that are stabilised with fly ash-based geopolymer at 6%, 12% and 18% respectively. The improvement in consolidation properties of fly ash-based geopolymer stabilised dredged mud sediment is attributed to the flocculated dredged mud slurry sedimentation pattern. Ganesalingam et al. (2013) proposed settling behaviour of soft soil slurry influences homogeneity and consolidation characteristics of the final sediment.

The results of this research study are comparable to the finding of Liu (2015). Liu (2015) has investigated the feasibility of stabilising loess with fly ash-based geopolymer binder and found binding effect of geopolymer gel contributes to improvements of the mechanical properties of loess. Salehi (2009) has revealed the lime modification of dredged mud slurry has resulted in flocculated sedimentation behaviour that improved permeability and coefficient of consolidation of the formed dredged mud sediment. The consolidation test results are consistent with the fly ash-based geopolymer stabilised dredged mud sediments compressibility results that are shown on Figure 6.4. The fly ash-based geopolymer stabilisation has reduced compressibility of stabilised dredged mud sediment (i.e. less volumetric strain). The dredged mud sediment volumetric strain is equivalent to the volume of pore water to be expelled out of the consolidating dredged mud sediment layer. Viz., reduced compressibility means less pore water to be expelled and shorter expulsion time which in turn leads to expedited consolidation, given the dredged mud sediment permeability remains unchanged.

The (c_v) and (m_v) values that were obtained from the Oedometer testing for the untreated and the fly ash-based geopolymer stabilised dredged mud sediments are used to estimate the permeability coefficient (k) analytically. Figure 6.7 (k vs log) curves summarise (k) values that were estimated at similar effective pressure ( ) and different fly ash-based geopolymer stabilisation percentages. The permeability (k) curves on Figure 6.7 indicate that the permeability of dredged mud sediment increases with the increase of fly ash-based geopolymer stabilisation percentage. For effective stress of 40 kPa, permeability (k) values of: 2.17 × 10^{-10} m/s, 2.2× 10^{-10} m/s, 2.7 ×10^{-10} m/s and 3.65 ×10^{-10} m/s are estimated for untreated, 6%, 12% and 18% fly ash-based geopolymer stabilised dredged mud sediments respectively. The noticed improvement in the permeability (k) is thought to be as result of the changes of dredged mud sediments microstructure that were caused by the fly ash-based geopolymer stabilisation. Pores and hollow cavities that are present in the fly ash-based geopolymer stabilised dredged mud sediments facilitate easy drainage of pore water during primary consolidation. Mitchell (1956) has advised grain size, pore size and microstructural arrangement of soil particles are among the factors that influence the permeability of a given soft soil. Existence of interconnected voids in soil media through which water can flow are what make a soil permeable (Das and Sobhan 2012).

Permeability is the soil parameter that measures rate of water drainage out of a soil layer such as dredged mud sediment when subjected to stress. By its very nature, the permeability of a soil is dependent upon water flow paths that are available in the soft soil matrix. Rajasekaran and Narasimha (2002) proposed that increased voids in soil lead to creating water flow channels that improve drainage properties of the soil which in turn increase its permeability. Where, Haase and Shanz (2016) have found addition of polymer to clayey soil creates preferential inter-unit flow paths within the clay-polymer composite that increase the permeability of the soil mixture. Beside the other microstructural alterations, the un-reacted and partially dissolved fly ash particles are also contributing to the permeability improvement. Fly ash has superior permeability properties in contrast to soft dredged mud sediment. Tu et al. (2007) has ascertained class F fly ash has hydraulic conductivity characteristic similar to that of very fine sands and inorganic silts.

6.6 Summary

The consolidation of thick layer of cohesive soft soils such as dredged mud sediments that have very low permeability could take decades as the expulsion of water from the soft soil pore spaces is slow process. This laboratory study has investigated the effect of the fly ash-based geopolymer binder on the consolidation behaviour of soft dredged mud that was obtained from the Port of Townsville. The consolidation behaviour of the untreated treated and the fly ash-based geopolymer stabilised dredged mud sediment specimens are investigated by studying their compressibility, consolidation, and permeability properties. From the results of this laboratory experimental study the following conclusions can be drawn:

- Fly ash-based geopolymer stabilisation of high water content soft dredged mud slurry produces stabilised dredged mud sediment that has improved compressibility, consolidation and permeability characteristics.
- The improvements in compressibility, consolidation and permeability characteristics of the fly ash-based geopolymer stabilised dredged mud sediment are attributed to the binding effect of the fly ash-based geopolymer gel and the accompanied changes in the stabilised dredged mud sediment microstructure.
- The fly ash-based geopolymer gel coating the dredged mud particles in the dredged mud slurry is considered to be the main factor that controls the geopolymer stabilisation process and the subsequent stabilised dredged mud sediment microstructure alterations.
- The laboratory experimental study results suggest the potential use of the fly based geopolymer paste as a sustainable binder to stabilise high water content soft dredged mud slurry such as that is used as fill material for land reclamation purposes.
- Besides improving the compressibility and consolidation properties of dredged mud sediment, fly ash-based geopolymer stabilisation of dredged mud also provides environmental benefit of beneficial usage of waste material such as fly ash in geopolymer synthesisation.
- A comparison of coefficient of consolidation (c_v) values obtained from the laboratory data and the field estimated (c_v), found the field estimated (c_v) values are higher than that were obtained from the laboratory testing.
- The variation between the field and laboratory obtained (c_v) values is primarily attributed to difference between the values of permeability that were estimated from one directional water flow in laboratory specimens and the multi-dimensional flow that occurs in the field.
- Differences in parameters of in-situ and laboratory soil specimens are also contribute to in-situ and laboratory (c_v) values.

Chapter 7: Case study - settlement analysis of the eastern reclamation area – the Port of Townsville

7.1 Introduction

The appropriateness of a soft soil stabilisation method is measured by the consolidation rate and the total settlement amount of the stabilised soft soil. To estimate the consolidation rate and settlement amount of fly are ash-based geopolymer binder stabilised dredged material, settlement of eastern reclamation area of the Port of Townsville is studied.

The Port of Land reclamation works at the Port of Townsville are started in early 1940's. Most of the infrastructure of the Port of Townsville is built on ground that was reclaimed using dredged material derived from its waters and rock material that was quarried from the nearby Pilots and Magazine hills. The Port of Townsville's eastern reclamation area is the most recent land reclamation works that was undertaken by the port. The successive maintenance and capital dredging campaigns for the last two decades have resulted in the deposition of over two million cubic metres of soft dredged material into the port's eastern reclamation area, thereby creating approximately 200 hectares of reclaimed land (Jaditager et al. 2014). The Port of Townsville's eastern reclamation area is located between the existing port infrastructure and the sea channel section of Ross River. Figure 7.1 shows the location eastern reclamation area, the port of Townsville's principal site for land based dredged material placement. The eastern reclamation area is created to accommodate future port infrastructure such as warehouses, office blocks, workshops, roads, railway, hardstands for cargo storage, and services corridors.

Figure 7.1 - Aerial view of the Port of Townsville's eastern reclamation area

Zhao et al. (2015) advised reclaimed lands are seriously affected by ground settlement episodes that are primary caused by unconsolidated fill material that results in severe damage to buildings and public infrastructure. The Port of Townsville's eastern reclamation area is expected to undergo a large degree of deformation due to the consolidation settlement of the soft dredged mud that is used as structural fill material and the underlying natural subsurface. Beside the challenge of high compressibility, land reclaimed with compressible dredged material would take decades to complete its primary consolidation process by natural means.

Ground improvement techniques are usually applied to enhance strength and compressibility characteristics, to expedite the lengthy consolidation duration, and allow early utilisation of the reclaimed land. To ascertain geotechnical properties of the dredged fill material and subsurface soil of the eastern reclamation area, the Port of Townsville has conducted a series of geotechnical site investigations and laboratory testing. Using soil parameters that were obtained from these previous geotechnical investigations and this experimental laboratory study, ground settlement analysis of the Port of Townsville's eastern reclamation area is conducted under a range of applied loadings conditions. The consolidation rates and the anticipated ground settlement amounts of untreated and 18% fly ash-based geopolymer stabilised land reclamation fill material were estimated.

The Port of Townsville's eastern reclamation area settlement analysis is undertaken to answer the questions of what is the amount of the anticipated settlement that would occur due to the loading and the time required by the reclaimed ground to complete its primary and secondary consolidation processes. The primary consolidation settlement of the reclaimed ground is mainly caused by dissipation of the excess pore water pressure of dredged mud sediment, where, secondary consolidation settlement (creep) is due to the rearrangement of dredged mud sediment particles. The estimated ground settlement values are to be used for refining the existing consolidation lead times guidelines, ground improvement methods selection, and to appreciate likely performance of the stabilised reclaimed ground. This chapter discusses the Port of Townsville's eastern reclamation area site description, geological settings, geotechnical site investigations, site categorization, assumptions that were made to allow a rational ground settlement analysis, settlement assessment method used, and the obtained results.

7.2 The Port of Townsville eastern reclamation area site description

The Port of Townsville eastern reclamation area is a 50-hectare land that was cut off from ocean by a perimeter rock wall. The eastern reclamation area has internal partition bunds to enable hydraulic placement of the dredged material, dewatering and tail water management. The internal partition bunds form several dredged material containment ponds that have been progressively filled with fine grained maintenance and capital dredging materials that was derived from the port's navigation channels, swing basin and berth pockets over the years. The dredge mud slurry is pumped through a pipeline into the dredged material containment ponds at multiple discharge points to minimise the land reclamation fill material segregation. Maximum dredged mud particles' settling is achieved by maximising the dredged mud slurry flow path through a network of weir boxes. The fine dredged material and tail water flow within the containment ponds is controlled by box weir boxes and the dredged mud slurry flow paths.

Prior to the construction of the Port of Townsville's eastern reclamation perimeter rock revetment, the top soft sediments on the sea floor were dredged to minimize potential settlement due loading induced from rock wall and the dredged fill material (Port of Townsville 2013). The construction of perimeter rock wall was started in 1982 and it was completed in 1992. The placement of dredged material commenced early 1993 and it is progressing up to date. The reclamation works are complete for some parts of the eastern reclaim area to reduced level of + 5.2 to +5.6 m, while reclamation operations are still progressing on other parts.

7.3 The Port of Townsville eastern reclamation area site geological settings

The geology of Townsville region comprises Quaternary aged alluvium and colluvium sediments underlain by Late-Palaeozoic age granite (Queensland Department of Mines 1986). The Port of Townsville's eastern reclamation area is not included on the Australia 1:250 000 geological series, Townsville Queensland Sheet SE 55-14, as the site was submerged at the time of the sheet preparation. Review of the Townsville geological map indicates the terrain to the south of the eastern reclamation area is to be underlain by Quaternary age estuarine deposits comprising mud, clay, silt and sand, then Permian age granite at depth of - 20 to - 23 m lowest astronomical tide (LAT) Figure 7.2. The near surface lithology of the Port of Townsville encompasses Holocene sediments more than 12,000 years old, including recent silt, mud and sand described as coastal tidal flats, mangrove flats and supratidal saltpans (Golder Associates 2008).

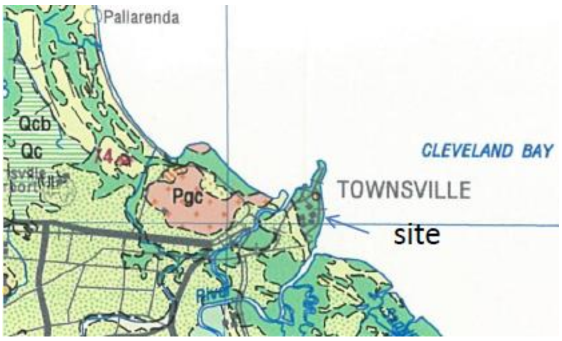


Figure 7.2 – Excerpt from Townsville geological map - Queensland State Government, Department of Mines (1986)

7.4 Site categorization of the eastern reclamation area – the Port of Townsville

Geotechnical site investigations and field observations indicated there is significant variability existed in the strength and composition of the materials of the Port of Townsville's eastern reclamation area. In order to allow a rational reclaimed ground settlement analysis and the subsequent ground treatment response, the eastern reclamation area was divided into eight areas (zones) that are considered likely to have similar settlement performance based on the available geotechnical site information. The eight areas are marked as area 1 to 8 as shown on Figure 7.3.

Figure 7.3 – Site categorization of the eastern reclamation area – the Port of Townsville

The site reclamation history of each area (pond) was established using dredge logs, reclamation progress reports, aerial photos, and geotechnical investigation reports. Each area was described by its site reclamation history information as shown on Table 7.1.

Table 7.1 - Characteristics of the eastern reclamation area site categories *(*Port of Townsville 2008*)*

Area	Area Description	Surface Reduced Level (m)
1	Dredge spoil treatment area	3.9
2	Stockpiled material	5.4
3	Stockpiled and dredged material	4.7
4	Material deposited 2005	4.6
5	Treated spoil containment	5.7
6	2005/2007 deposited material	4.2
7	2007/08 deposited material	3.9
8	2007/2008 deposited material	3.9

The functional requirement of the eastern reclamation area is for light industrial use. However, as a cost saving measure, the Port of Townsville is preparing the reclaimed land to light industrial standards, leaving the ground improvement for any heavier load conditions to later stage when the details of the reclaimed land utilisation and type of structures to constructed are available.

7.5 Geotechnical site investigations of the eastern reclamation area – the Port of Townsville

The Port of Townsville's eastern reclamation area which reclaimed using soft dredged mud slurry has took more than decade to self-weight consolidate and gain sufficient stiffness to be accessible by geotechnical investigations plant and personnel. To ascertain properties of the reclaimed land fill material, and the underlying subsurface, the Port of Townsville in collaboration with its geotechnical consultants has conducted series of geotechnical site investigations and laboratory testings on its eastern reclamation area. Data gathered from these geotechnical site investigations has been analysed to identify values of soil parameters required for the reclaimed land settlement estimations and consolidation modelling.

The geotechnical site investigations that were undertaken on the eastern reclamation area have showed that subsurface conditions encountered comprise dredged material filling of low to high plasticity clays/silts, sandy clays, silty sands and sand to approximately top 1 to 5.6 m. The dredged fill material is underlain by about 1 to 2 m layer of recent seabed sediments of alluvial deposits that are generally contain mixture of very soft to soft clays/silts and very loose to medium dense sand with shell fragments and organic material. The layer below the sea bed is found to be consolidated older stiff to hard clays, silty clays and sandy clays and medium dense to very dense clayey sands and sands to depth of 14.96 to 16.52m. The consolidated older layer is underlain by deeper residual soils and granite/basalt rock (Douglas Partners 2009).

7.6 The Port of Townsville eastern reclamation area loading conditions

The loading conditions of the Port of Townsville's eastern reclamation area were determined from its intended use. The specific details of the intended structures to be constructed on the Port of

Townsville's eastern reclamation area will only be available at the actual development time. Accordingly, the Port of Townsville prepares its eastern reclamation area preliminary design for construction surcharge of 40kPa as general design load. For further reclaimed ground improvement to be applied to the required loading conditions and ground performance when the details of the specific structure to be founded on the reclaimed ground are available (Jaditager et al. 2015b). Typically, the Port of Townsville's eastern reclamation area is required to support the load cases that are anticipated to be imposed by the following structures:

- Transit and storage warehousing;
- Office blocks;
- Plant and equipment workshops/yards;
- Heavy pavements such as container stacking yards (Figure 7.4);
- Access roads and rail way tracks; and
- Services corridors.

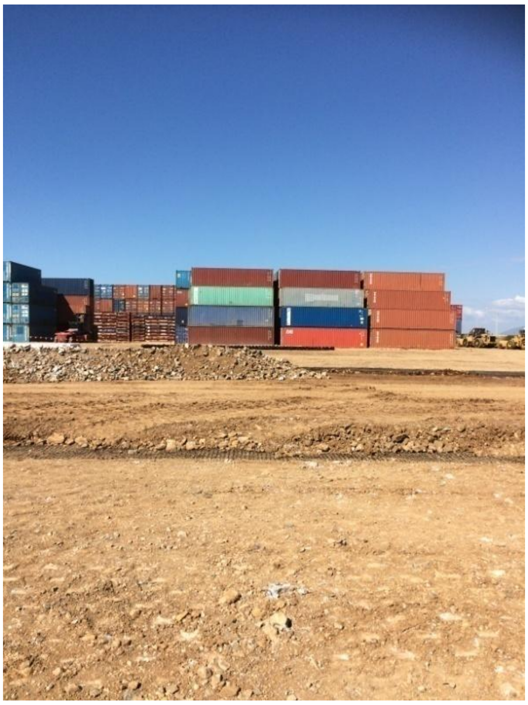


Figure 7.4 – Temporary container storage yard eastern reclamation area – the Port of Townsville

The loading sequence is assumed to be initial filling with dredged to reduced level + 5.5m of an average bulk density of 20 KN/m3, allowed to complete preliminary consolidation, followed by additional loading of 40 kPa that is expected to be imposed by future development. The secondary consolidation is assumed to commence after primary consolidation is 90% complete. The reclaimed ground performance requirements are formulated from design load of the structures to be constructed on the reclaimed land, maximum allowable settlement of these structures, safety against slope failure and land liquefaction potential (van't and van der kolff 2012).

7.7 Settlement analysis method

According to Katagiri and Terashi (2001), the settlement behaviour of a reclaimed ground depends naturally on the characteristics of the land reclamation fill material and elapsed time. The first step in soft ground settlement analysis is a careful study of the applied load, selection of appropriate soil parameters and components of the anticipated total settlement. Accuracy of any soft soil settlement estimate is driven by reliability of the selected soil parameters and soil loading profile.

While undertaking settlement analysis of the Port of Townsville's eastern reclamation area the intended use of the reclaim ground and the subsequent reclaimed ground loading scheme are considered. The settlement performance of each of the eight areas, the underlying seabed and the natural stiff clay was calculated using soil parameters that were obtained from the results of geotechnical site investigations and laboratory testing. Statistical assessment has been undertaken on the actual geotechnical data collected for each relevant soil parameter to provide the most likely values. Empirical correlations were used to allow calculation of the soil parameters that have not been directly tested (Jaditager et al. 2015a). To account for potential of variations in settlement performance within a selected area due to variability in the dredged material, geotechnical data considered to give largest settlement estimate is chosen for settlement calculation. Some adjustments on geotechnical properties of the land reclamation dredged material and the underplaying natural soil were made to account for differences expected between laboratory measured and in-situ obtained soil properties.

During the primary consolidation of a saturated clayey soil such as dredged mud sediment, the consolidation settlement (deformation) is due to the water drainage out of the soil void as the pore water pressure dissipates. Where, for the secondary compression settlement, the rate of void ratio reduction is controlled by the rate of compression in soft soil matrix. For reclaimed ground settlement analysis, the geotechnical parameters for both the land reclamation site natural subsoil and the fill material are required. The geotechnical properties of the soil that are used for the Port of Townsville's eastern reclamation area settlement analysis are shown on Table 7.2.

Table 7.2 - Soil parameters used for settlement analysis

Soil Type	$C_c/(1+e_0)$	c_v (m^2/year)	$C_\propto/((1+e_p)$
Untreated soft clayey dredged mud	0.25	0.6	0.01
18% geopolymer stabilised dredged mud	0.25	1.8	0.01
Natural soft/firm clay	0.25	7	0.01
Medium dense sands	0.01	50	0

Terzaghi's 1943 one-dimensional consolidation theory was used to assess the expected primary and secondary consolidation settlement. The coefficient of vertical consolidation (c_v) is determined using equation (2.12) Chapter 2. For the horizontal (radial) drainage condition, it is assumed that the marine sediment layers will exhibit relatively isotropic deformation behaviour as outlined by Lee et al. (1999).

Total settlement (S_T) of soils both in the short-term and over a nominal period of 25 years is calculated as the sum of: immediate settlement (S_i), primary consolidation settlement (S_c), and secondary consolidation settlement (S_{sc}) equation 7.1.

$$S_T = S_i + S_c + S_{sc} \qquad 7.1$$

When foundations are constructed on very compressible clayey soil, the consolidation settlement can be several times greater than the immediate (elastic) settlement (Das and Sobhan 2012). Rankine (2007) has reported the consolidation phase contributes the most significant portion of settlement soft soils such as clays. The immediate settlement of cohesive soils is relatively small part of the total vertical movement, as such; a detailed immediate settlement study is seldom justified unless the intended structures to be constructed are highly sensitive to distortion (Patrick 2003). As the functional requirement of the Port of Townsville's eastern reclamation area is to be used for port related infrastructure that tolerate some deformation, the immediate settlement component is assumed to be negligible. The immediate one-dimensional consolidation settlement of saturated cohesive soil such as clays is negligible because of the low compressibility of the pore water, equation 7.2.

$$S_i \approx 0 \tag{7.2}$$

Thus, the total time dependent settlement of the soft reclaimed ground is the sum of: Primary settlement and secondary compression (equations 7.3).

$$S_T = S_c + S_{sc} \tag{7.3}$$

Primary consolidation settlement (*Sc*) results from the time dependent pore water expulsion and the subsequent reduction in void ratio of the soft reclaimed ground fill material and the subsurface due to effective stress that is caused by loading, equation 7.4.

$$S_c = \frac{c_c}{1+e_0} H \log\left(\frac{\sigma_0' + \Delta\sigma'}{\sigma_0'}\right) \tag{7.4}$$

Where c_c is compression index, e_0 is initial void ratio, H is thickness of soil layer, σ_0 is initial effective stress and $\Delta\sigma'$ is the change in effective stress.

For the secondary compression settlement (creep) (S_{sc}), it occurs as result of time dependent rearrangement/adjustment of soil particle under constant effective stress conditions, equation 7.5

$$S_{Sc} = \frac{C_\propto}{1+e_p} \text{H} \log\left(\frac{t_2}{t_1}\right) \tag{7.5}$$

$(C_\propto)$ is secondary compression index, $(e_p$) is void ratio at the end of primary consolidation, where, $(t_{1)}$ is and $(t_2$) are time. The secondary compression index ($C_\propto$) is function of change in void ratio $(\Delta e$) and time(*t*). Where, $(C_\propto)$ can be estimated using equation 7.6.

$$C_\propto = \frac{\Delta e}{\Delta \log t} \tag{7.6}$$

The coefficient of consolidation c_v of a soft soil such as land reclamation dredged material is estimated from the soft soil specimen's deformation versus elapsed time data that were recorded during one-dimensional consolidation test, equation 7.7. Taylor (1942) square-root of time consolidation curve fitting method is used to determine the dimensionless time factor(T_v).

$$T_v = \frac{4c_v t}{H^2} \tag{7.7}$$

(T_v) is time factor, and c_v is coefficient of vertical consolidation

By substituting equations 7.4 and 7.5 into the total settlement equation 7.3 yields equation 7.8.

$$S_T = S_c + S_{sc} = \frac{C_c}{1+e_0} H \log\left(\frac{\sigma_0' + \Delta\sigma'}{\sigma_0'}\right) + \frac{C_\propto}{1+e_p} H \log\left(\frac{t_2}{t_1}\right) \tag{7.8}$$

7.8 Settlement analysis results

The Port of Townsville's eastern reclamation area settlement estimates for dredged material filling to surface level (RL) of 5.5 m, allowing primary consolidation to complete, then followed by application of development project loads of 40kPa are presented in tables 7.2, 7.3 and 7.4 respectively.

Table 7.3 - Settlement estimates (mm) for 40 kPa loading after filling to RL 5.5m (untreated)

Soil Property	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Area 7	Area 8
S_c	170-200	160-220	290-320	150-180	220-240	140-160	140-170	120-150
T_{90}(month)	7	12	6	8	7	8	8	8
S_{sc}(25 yrs.)	50-70	50-90	140-160	60-90	140-170	60-70	60-70	50-80
S_T(25 yrs.)	220-270	210-310	430-480	210-270	360-410	200-230	200-240	170-230

Table 7.4 - Settlement estimates (mm) for 40 kPa loading after filling to RL 5.5m (18% geopolymer stabilised)

Soil Property	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6	Area 7	Area 8
S_c	110-150	120-160	260-290	100-140	180-210	110-140	100-130	100-120
T_{90}(month)	3	6	2	3	4	5	4	4
S_{sc}(25 yrs.)	40 -70	30-70	110-140	50-80	100-120	50-70	40-70	40-70
S_T(25 yrs.)	150-220	150-230	370-420	150-220	280-330	160-210	140-200	140-190

Discussion and conclusion

The geotechnical site investigations results and the land reclamation history of the Port of Townsville's eastern reclamation area enabled the site to be categorised into areas that are considered likely to have a similar settlement performance. The site history of each area (dredged mud containment pond) was established by analysing dredge logs, reclamation progress reports, and aerial photos. Information gathered from the field investigations and laboratory testings conducted on the eastern reclamation area has informed the most likely values of soil parameters of the reclaimed land fill and the subsurface materials that are required for ground settlement analysis.

The eastern reclamation area settlement analysis outcome will assist the Port of Townsville to refine its established consolidation lead times guidelines, ground improvement methods selection and to appreciate the likely performance of the treated ground. The port has successfully stabilised its reclaimed land by applying ground improvement techniques ranging from surcharging, lime stabilisation, to lime column and stone column replacement/ dynamic compaction in the past. Guided by structures sensitivity to ground deformation and the performance of the improved ground, the Port of Townsville had constructed different structures on shallow and deep foundations.

From the Port of Townsville's eastern reclamation area settlement analysis study, the following conclusions can be drawn:

- The consolidation rates were observed to be relatively fast which can be attributed to the silt and sand component in the compressible dredged material layers facilitate the pore water dissipation process.
- The estimated settlement magnitudes were found to be manageable by stabilising the dredged fill material with fly ash-based geopolymer binder.
- The fly ash-based geopolymer stabilised reclaimed ground can adequately support the loading to be imposed by the future port infrastructure that is anticipated to be constructed on the eastern reclamation area.

- To account for the differential settlement of the reclaimed ground that is anticipated to be caused by land reclamation fill material variability, the foundation design is to be approached in such a way that the stability of soft land reclamation fill material and its differential settlement to be maintained at all times.

Chapter 8: Summary, conclusion, and recommendations

8.1 Summary

Soft soil stabilisation techniques are implemented to address unfavourable geotechnical properties of soft soil that was formed by natural processes of rock weathering, transportation, deposition, sedimentation and self-weight consolidation. However, for manmade soft grounds such as land reclaimed by soft dredged material, there is a chance to manipulate the microstructure of the intended land reclamation fill material that controls its compressibility and consolidation characteristics. One way of influencing the microstructure of the to be formed land reclamation fill material is by controlling the sedimentation behaviour of the high-water content dredged mud slurry before it turns into land reclamation fill material.

This research study has investigated the feasibility of stabilising high-water content dredged mud while it is still in slurry form using the fly ash-based geopolymer binder. The fly ash-based geopolymer binder is added to high water content dredged mud slurry in order to flocculate the dredged mud particles in the slurry and control the sedimentation behaviour of the stabilised dredged slurry. The fly ash-based geopolymer is chosen as dredged mud stabilisation binder for the fact that it is not sensitive to high water content nature of the dredged mud slurry, environmentally friendly and for its cost effectiveness.

To ascertain the feasibility of stabilising soft dredged mud slurry with the fly ash-based geopolymer binder, the study has examined the sedimentation and consolidation behaviours of fly ash-based geopolymer stabilised dredged mud as well as its mineralogy and microstructure. The sedimentation behaviour of the fly ash-based geopolymer stabilised dredged mud slurry influences its microstructure and subsequent compressibility and consolidation characteristics of to be formed fly ash-based geopolymer stabilised dredged mud sediment.

The research study found t it is feasible to stabilise high water content dredged mud slurry using fly ash-based geopolymer binder. The fly ash-based geopolymer stabilisation has exacerbated flocculated settling pattern of the stabilised dredged mud slurry and influenced the sedimentation behaviour of the stabilised dredged mud slurry. In turn, the exacerbated flocculation settling has influenced the sedimentation behaviour of the dredged mud slurry and resulted in extended flocculation stage, shorter settling stage and reduced the overall sedimentation duration. The flocculated sedimentation behaviour has altered the microstructure of the resulted fly ash-based geopolymer stabilised dredged mud sediment. The microstructure of the fly ash-based geopolymer stabilised dredged mud sediment is found to have a rough and porous morphology with hollow cavities, larger particles aggregation and reduced desiccation shrinkage cracks. In term of consolidation behaviour of the fly ash-based geopolymer stabilised dredged mud sediment, it is noticed the fly ash-based geopolymer stabilisation has produced stabilised dredged mud sediment that has improved compressibility, consolidation and permeability characteristics.

8.2 Conclusion

The Port of Townsville dredged mud slurry was stabilised with fly ash-based geopolymer binder and the influence of geopolymer stabilisation on the sedimentation and the consolidation behaviour of soft dredged mud was investigated. The sedimentation behaviour of the untreated and the fly ash-based geopolymer stabilised dredged mud slurry was examined by investigating the settling patterns, sedimentation stages, settling curves and sedimentation duration of the geopolymer stabilised dredged mud slurry. Where, the consolidation behaviour of the untreated and the fly ash-based geopolymer stabilised dredged mud sediments are investigated by studying their compressibility, void ratio, consolidation, and permeability properties. The study also looked at the mineralogy and microstructure of the untreated and the fly ash-based geopolymer stabilised dredged mud sediments to detect potential of new minerals formation or microstructural change due to the fly ash-based geopolymer stabilisation. From the findings of this experimental research study, the below conclusions can be drawn:

8.2.1 Dredged mud slurry stabilisation with fly ash-based geopolymer binder

The results of the research study showed it is feasible to use fly ash-based geopolymer binder as a sustainable binder to stabilise high water content soft dredged mud slurry such as that is used for land reclamation projects. The fly ash-based geopolymer gel coating the dredged mud particles in the slurry was found to be main factor that controls the fly ash-based geopolymer stabilisation and the associated stabilised dredged mud sediment microstructure alterations. Besides improving the geotechnical properties of the stabilised dredged mud sediment, the fly ash-based geopolymer stabilisation of dredged mud also provides environmental benefit of beneficial usage of waste material such as fly ash in geopolymer binder synthesisation.

8.2.2 Sedimentation behaviour of fly ash-based geopolymer stabilised dredged mud

The study found both untreated and the fly ash-based geopolymer stabilised dredged mud slurries have exhibited flocculated sedimentation behaviour, with flocculation increasing with the increase of fly ash-based geopolymer stabilisation percentage. The fly ash-based geopolymer gel coating dredged mud particles in the slurry has led to an exacerbated flocculated settling behaviour. The study also found the fly ash-based geopolymer stabilisation has increased the flocculation time of geopolymer stabilised dredged mud particles, and reduced particles settling time. The fly ash-based geopolymer stabilisation has reduced the overall dredged mud slurry sedimentation duration and increased the final sediment column height (volume). On land reclamation with soft dredged mud project site, expedited sedimentation leads to less tail water management, quicker commencement of self-weight consolidation process that yields more stable ground and earlier utilisation of the reclaimed land.

8.2.3 Mineralogy of fly ash-based geopolymer stabilised dredged mud sediment

The comparison of the chemical phase composition of the untreated and the fly ash-based geopolymer stabilised dredged mud sediments has found no notable variations between the untreated and the fly ash-based geopolymer stabilised dredged sediments in mineralogical terms. Thus, there is no fly ash-based geopolymer stabilisation induced new chemical elements formation in the stabilised mud sediments. The lack of significant elemental differences between the untreated and the stabilised dredged mud sediments means there is no direct correlation between the fly ash-based geopolymer stabilisation and the mineralogy of the stabilised dredged mud. This confirms that the fly ash-based geopolymer gel is coating dredged mud particles in the settling dredged mud slurry is the only mechanism governs the dredged mud slurry stabilisation with fly ash-based geopolymer binder.

8.2.4 Microstructure of fly ash-based geopolymer stabilised dredged mud sediment

Scanning electron microscopy SEM images has shown significant microstructural variances between the untreated and the fly ash-based geopolymer stabilised dredged mud sediments. Compared to the untreated, the fly ash-based geopolymer stabilised dredged mud sediment has exhibited a coarser microstructure and surface structure that is predominately featured to be rough, porous with hollow cavities and randomly oriented clay particle aggregations that are bigger in size. The fly ash-based geopolymer gel connector, undissolved/partially dissolved fly ash particles, scattered silt and clay particles are also apparent on the microstructure of the fly ash-based geopolymer stabilised dredged mud sediment. The microstructure of the fly ash-based geopolymer stabilised dredged mud sediments also shown reduced or no desiccation shrinkage cracks.

The microstructural changes on the stabilised dredged mud sediments are attributed to mud slurry flocculation regime that is exacerbated by geopolymer gels coating dredged mud particles in the high-water content slurry during the stabilisation process. The study concluded the fly ash-based geopolymer stabilised dredged mud sediments particle aggregation sizes, pore number and size are increased with the increase of fly ash-based geopolymer stabilisation percentage.

8.2.5 Consolidation behaviour of fly ash-based geopolymer stabilised dredged mud sediment

The fly ash-based geopolymer stabilisation of high water content soft dredged mud while it is still at slurry form produces fly ash-based geopolymer stabilised dredged mud sediment that has improved compressibility, consolidation and permeability. The improvements in compressibility, consolidation and permeability characteristics of the geopolymer stabilised dredged mud sediment are owed to the binding effect of the fly ash-based geopolymer gel and the accompanied changes in the stabilised dredged mud sediment microstructure.

A comparison of coefficient of consolidation (c_v) values obtained from the laboratory data and the field investigations found that (c_v) values that were obtained from the field investigations are higher than that were obtained from the laboratory testing. The variation between the field and laboratory obtained (c_v) value is attributed primarily to site material variability and difference between the laboratory obtained permeability and on-site fill material permeability values. The laboratory computed permeability simulates one directional (vertical) water flow in laboratory specimens, where the actual on site pore water dissipation is both vertical and radial flow.

8.3 Practical implications of the study findings on land reclamation by soft dredged mud slurry project site

On land reclamation with soft dredged mud slurry project, stabilising dredged mud while it is still at slurry form mean there is potential of controlling sedimentation behaviour of the stabilised dredged mud slurry that influences the geotechnical properties of the resulting land reclamation fill material. The sedimentation behaviour of soft soil slurry closely linked to the microstructure, homogeneity and consolidation characteristics of the final sediment to be formed by the sedimentation process. The findings of this experimental study have the following practical implications:

- Shorter sedimentation duration (expedited sedimentation) means less tail water management, less environmental issue such as odors, quicker commencement of self-weight consolidation process that yields more stable ground in shorter time (i.e. earlier utilisation of the reclaimed land)
- Less compressible fill material and shorter primary consolidation duration of land reclamation fill material mean the resulting reclaimed land has favorable geotechnical properties and can be developed in shorter time frame.
- The fly ash-based geopolymer stabilised dredged mud sediment with improved shrinkage resistance reduces the risk of reclaimed ground shrinkage cracking that causes pavement and shallow foundation damages.
- Environmental benefit of reducing industrial by product waste such as fly ash and reducing the cost of fly ash storage lagoons construction, maintenance and management.

- Feasibility of stabilising soft dredged mud slurry using the fly ash-based geopolymer adds one more stabilisation method to the existing soft dredged material stabilisation means
- Fly ash-based geopolymer stabilisation of soft dredged mud while it is still in slurry form encourages early intervention approach of soft dredged mud stabilisation, opens up the potential of new dredged material stabilisation material.

8.4 Recommendations for future research

This experimental study has focused on the feasibility of stabilising soft dredged mud while it is in its slurry form using fly ash-based geopolymer binder. To ascertain the treatability of high water content dredged mud slurry with fly ash-based geopolymer binder, the sedimentation and consolidation behaviours, as well as the mineralogy and the microstructure of the untreated and the fly ash-based geopolymer stabilised dredged were investigated. In absence of previous dredged mud stabilisation with fly ash-based geopolymer material in the published literature, geopolymer specifications that are used in geopolymer concrete industry were adopted for this experimental study. Throughout this research study, several questions were arisen, some of which are potential future research avenues. The findings of this research study can be used as basis for the following recommended future research areas:

8.4.1 Strength properties of fly ash-based geopolymer stabilised dredged mud sediment

Soil strength is among the soil geotechnical parameters that contribute and guide suitability of the soil to support foundations. Soft soil strength property is as important as its compressibility and consolidation characteristics. This research study has investigated sedimentation and consolidation behaviours of fly ash-based geopolymer stabilised dredged mud slurry by studying the settling patterns, sedimentation stages as well as the compressibility and consolidation characteristics of the geopolymer stabilised dredged mud sediment. To decide construction of structure on reclaimed land, the strength properties of reclaimed ground is to be considered beside compressibility and consolidation characteristics of the land reclamation fill material. Though it is known that less compressible soils have better strength, studying the strength properties of the stabilised dredged mud sediment, alongside its compressibility will provide a broader picture of the geotechnical properties of the fly ash-based geopolymer stabilised dredged mud.

8.4.2 Influence of aluminosilicate source material on the geotechnical properties of geopolymer stabilised dredged mud

Fine grain class F fly ash was used as aluminosilicate source material and precursor for geopolymer synthesisation in this study. It is worthwhile to investigate comparative aluminosilicate source materials such as metakaolin, granulated blast furnace slag or volcanic ashes and study the influence of these alternatives aluminosilicate source material on the geotechnical properties of geopolymer stabilised dredged mud sediment.

8.4.3 Influence of alkali activator solution on the geotechnical properties of geopolymer stabilised dredged mud

Strong alkali activator is vital for dissolving the aluminosilicate source material that forms the geopolymer precursor during the geopolymer synthesisation process. 98% purity sodium hydroxide(NaOH) pallets that are dissolved in fresh water was used as alkali activator liquid to dissolve the aluminosilicate source material, the class (F) fly ash to form the geopolymer binder that was used to stabilise the dredged mud slurry. Investigation of an alternative alkali activator liquid like Potassium Hydroxide (KOH) to dissolve the aluminosilicate source may result in geopolymer stabilised dredged mud sediment with superior geotechnical properties compared to that of sodium hydroxide dissolved geopolymer binder.

8.4.4 Influence of geopolymer synthesisation mix design on the geotechnical properties of geopolymer stabilised dredged mud

Alkali activator solution sodium hydroxide (NaOH) solution preparation ratio of 32 grams to one litre of fresh water, sodium hydroxide (NaOH) fly ash 3:1 by weight and the geopolymer preparation boundary condition that are used in this study were adopted from the geopolymer concrete literature. In this study, the dredged mud slurry to the fly as-based geopolymer binder mixing ratio of 6%, 12%

and 18% by weight were used. Investigating the influence of different alkali activator liquid and geopolymer preparation mix designs on the geotechnical properties of the geopolymer stabilised dredged mud will advance and refine the dredged mud stabilisation with geopolymer binder studies.

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