PROGRESS IN ENGINEERING APPLICATION AND TECHNOLOGY
e-ISSN: 2773-5303

PEAT

Vol. 7 No. 1 (2026) 154-163
https://publisher.uthm.edu.my/periodicals/index.php/peat

1-D Consolidation Characteristics of Stabilised Dredged Marine Soils as Engineered Backfills

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DOI: https://doi.org/10.30880/peat.2026.07.01.019

Article Info

Received: 12 January 2026
Accepted: 20 February 2026
Available online: 25 May 2026

Keywords

Dredged Marine soil, consolidation, polymer modified cement, engineer backfill, sustainable construction

Abstract

The Dredged Marine Soils (DMS) products that are by-products of navigational maintenance are usually considered to be geo-waste products due to their high moisture content, extreme compressibility and low shear strength. The use of such sediments as engineered backfill that could be used sustainably is becoming a more urgent requirement in order to reduce the negative environmental impact by offshore disposal and to deal with the alarming loss of inland sources of sand. Having a good feel of the one dimensional (1-D) behavior of consolidation is important to such materials, because the long-term behaviour in settlement is what directly determines serviceability to structures and adherence to high standards of infrastructure. This paper explores the possibility of regional DMS stabilization basing on bulk samples of four strategic points in Malaysian localities, namely, Kuala Kedah, Kuala Perlis, Lumut, and Endau. After physical characterization, samples were stabilized with 5% Ordinary Portland Cement (OPC) and a novel Polymer Modified Cement (PMC) 4% and then subjected to the oedometer testing, as per BS 1377: Part 5. The results obtained indicate that untreated DMS has extreme compressibility (Cc = 0.37 -0.47) and slow drainage. Although 5% OPC enhanced stiffness, it created a pore-clogging effect at high stress inhibiting consolidation. The 4% PMC treatment in contrast, demonstrated a technical breakthrough in which Cc was reduced up to 99.3% and a rigid skeleton of soil with increased consolidation rates was formed. Using simulations of performance, a 5-meter reclamation layer of PMC-treated DMS would settle within less than 10 days, with a comfortable margin of 100 mm which is the allowable settlement of the Public Works Department (JKR) Malaysia. The findings show that optimized PMC stabilization makes problematic geo-waste a high-performance, time-efficient, and sustainable resource in construction.

1. Introduction

The dredging activities of Malaysia especially at the river mouths and ports of Kuala Perlis, Kuala Kedah, Lumut and Endau are necessary because they maintain navigational depths and facilitate the maritime traffic. Nevertheless, the processes produce huge amounts of excess Dredged Marine Soils (DMS) which has conventionally been mentioned under geo-waste. Those materials are generally soft clays and silts which are highly moist in nature and which have low shear strength and extreme compressibility, so they are intrinsically inappropriate in the form of structural construction[10]. The historical tendency took the form of offshore disposal or landfilling, which have become increasingly limited by the lack of space, the increase in the environmental concerns, and the tightening of the international regulations.

The technical challenge of re-purposing DMS lies in the fact that it is highly compressible with a very fine-grain size. According to the recent research on the marine sediments of the Straits of Melaka, untreated DMS at all times does not correspond to the Public Works Department (JKR) Malaysia requirements on structural backfill. Under the JKR guidelines, engineered road embankment fills shall not be more than a total of 100 mm and 25 mm/m differentially[7]. Moreover, untreated high-plasticity clays may require decades to reach 90 percent primary consolidation, a time lag that can result in the necessity to use costly soil improvement methods including the Prefabricated Vertical Drains (PVDs) or vacuum preloading[1]. This is made afar by increased environmental and economic costs of traditional sand mining, and therefore, the construction industry needs to know the sustainable use of DMS.

Although the use of ground improvement through chemical stabilization with the application of cementitious binders has been successful, an important research gap is associated with the consolidation behavior of stabilized DMS in the Malaysian environment. Another typical option is Ordinary Portland Cement (OPC), which usually causes a so-called clogging effect at elevated pressure increments. It takes place when the hydration products such as Calcium-Silicate-Hydrate (C-S-H) gels get into the soil micropores, limiting the water dissipation inside the pore inadvertently reduces the rate of consolidation (Cv). In response to this, a new practice has risen namely the utilization of Polymer Modified Cement (PMC). The structural strength of the cement is because PMC stabilization is done using a dual-bonding mechanism cement hydration, whereas the flexibility and coating of the particles is done using polymer film.

This research aim is to examine the one-dimensional (1-D) consolidation properties (Cc, Cv,σ'p) of the regional Malaysian DMS stabilized with 5% OPC and 4% PMC. Through several assessments of the vertical loading of sediments, the study will offer fundamental information on how to convert the challenging geo-waste into a high performance engineered backfill. The given transition helps to facilitate the shift to sustainable geotechnical principles, as it allows the adherence to the requirements of the JKR design standards and contributes to the principles of the circular economy by reusing waste materials available locally.

2. Materials and Methods

The experimental program was systematically structured to evaluate the transformation of Dredged Marine Soils (DMS) from a problematic "geo-waste" into a high-performance engineered backfill. This research was conducted in four distinct stages: material acquisition and physical characterization, chemical stabilization, one-dimensional (1-D) consolidation testing, and microstructural analysis. All testing procedures were strictly adhered to the British Standard BS 1377: 1990 series and BS EN ISO standards to ensure the accuracy and reproducibility of the geotechnical results.

2.1 Material acquisition and sampling

Samples of bulk sediments were collected at four strategic coast points namely Kuala Kedah (KK), Kuala Perlis (KP), Lumut and Endau to show the regional variability of marine sediments in Malaysia. The acquisition was strictly done in close cooperation with the Marine Department Malaysia (Jabatan Laut Malaysia, JLM) so that the sediments could be representative of active maintenance dredging areas. The sampling was performed by a mechanical clamshell dredger (grab dredger) which was placed in a barge, a technique chosen as opposed to hydraulic suction to avoid the removal of fine particles and the material to be sampled to represent the in-situ moisture and particle size distribution. The wet soil samples retrieved in the seabed were placed in heavy-duty plastic samples and hermetically sealed to avoid the loss of moisture and to a minimum of geochemical oxidation on the sample during transportation to the Geotechnical Laboratory in University Tun Hussein Onn Malaysia (UTHM).

Fig.1 Sampling location and material acquistion

2.2 Physical index properties testing

First stage geotechnical characterization was done to have a baseline of predicting soil behavior under the structural loading. Particle Size Distribution (PSD) was calculated by using wet sieving by using a 63 μm sieve (BS 1377: Part 2: 1990) and hydrometer analysis using Stokes law to separate the silt and clay particles. It is worth noting that, the hydrometer observation time was maintained at two months in order to record the high-resolution settling profile of the ultra-fine colloidal clay fractions that normally control long-term consolidation. The Liquid Limit (LL) and Plastic Limit (PL) were determined using the Casagrande technique to determine the plasticity and moisture sensitivity of the soil (BS 1377: Part 2). Other baseline tests were Specific Gravity (Gs) through pycnometer method to identify mineral composition and Standard Proctor Compaction (BS 1377: Part 4: 1990) to know the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC).

2.3 Specimen Preparations and Stabilizations

Two regimes of binders were compared with dry untreated controls of 5% Ordinary Portland Cement (OPC) and an experimental 4% Polymer Modified Cement (PMC) by dry weight. The dosage of 5% OPC was selected to surpass the original intake of lime limit in marine soils, and the dosage of 4% PMC was set to form a polymer film effectively to enhance the ductility. The specimens were prepared by the reconstituted process at a desired moisture content that was rigorously established at 1.0 x LL of the original soil in order to reproduce the slurry-like material that was in the state of freshly dredged. After a wet mixing of the samples to replicate field Deep Mixing Methods (DMM), stabilized samples were poured into the rings of consolidation, covered with Cling wrap, and placed in airtight bags. These samples were kept under a limited moisture in a humidity-controlled chamber at 27+- 2 C, over a period of 7 days to cure the cement, and also to permit the formation of the polymer film network.

2.4 One-Dimensional Consolidation Testing

The main performance assessment was the One-Dimensional Consolidation (Oedometer) Test which was undertaken according to BS 1377: Part 5: Standard fixed ring oedometer cell was set up with cured specimens using twice the drainage under saturated porous stones and Whatman No. 54 filter papers to keep the fines out. The cell was saturated with distilled water to ensure complete saturation within the period of conducting the test. The specimens were put through a rigorous incremental loading process of 5, 10, 20, 40, 80, 160, 320, 640 and 1280 kPa respectively with each intrusion taking 24 hours to ensure that the primary consolidation process had been completed. This wide range of stress enabled the determination with accuracy of the Compression Index (Cc) data of the e-log σ' curve and Coefficient of Consolidation (Cv) data of the Casagrande logarithm of time.

Fig.2 One-dimensional consolidation (oedometer) setup

2.5 Summary of Experimental Program

The logical progression of the laboratory testing regime, from raw material characterization to optimized engineering design, is summarized in Table 1. This structured framework ensures that the derived engineering parameters meet the Public Works Department (JKR) Malaysia specifications for engineered backfills, specifically targeting an allowable settlement of less than 100 mm.

Table 1: Summary of Laboratory Test and Derived Engineering Parameters

Research Stage	Laboratory Test	Standard Reference	Key Parameters & Result
Stage 1: Physical Characterization	PSD (Sieve & Hydrometer)	BS 1377: Part 2	Fines content (%), Gradation curves
	Atterberg Limits (LL,PL)	BS 1377: Part 2	Plasticity Index(Ip), Classification
	Specific Gravity (Gs)	BS 1377: Part 2	Particle density for phase relationship
	Standard Proctor Compaction	BS 1377: Part 2	Maximum Dry Density (MDD),OMC
Stage 2: Baseline Mechanical	1-D Consolidation	BS 1377: Part 4	Initial Void Ratio (e0),Cc and Cv
Stage 3: Stabilization Performance	5% OPC Stabilization	BS 1377: Part 5	Yield stress (σ'p), Pore-clogging analysis.
	4% PMC Stabilization	BS 1377: Part 5	"Infinite" Cv, Rigid skeleton Cc

3. Physical Characterization of Regional DMS

The physical and index properties of natural Dredged Marine Soils (DMS) serve as the essential baseline for predicting geotechnical behavior under structural loading. Understanding these site-specific characteristics is vital for anticipating the soil's response to chemical stabilization.

3.1 Particle Size Distribution and Textural Variability

Gradation of soil particles becomes one of the major defining factors of hydraulic and mechanical soil behaviour that directly affect such parameters like permeability, drainage rate and compressibility [1]. The analysis of the Particle Size Distribution (PSD) indicated that there was a serious geotechnical difference between the sediments in the north region and the southern/western sediments, which is represented in Fig. 3. Accurate comparison reveals that northern sediments of Kuala Kedah (KK) and Kuala Perlis (KP) are majorly fine-grained with their material content passing through the 63mm sieve at 96.64 and 90.18 respectively. It is this prevailing character of the clay-silt element, which is the root cause of the extreme water-holding power and extreme plasticity in these northern areas. By comparison, the samples at Lumut and Endau were much coarser with 53.35% and 74% sand-sized fractions, respectively. These drastic textural variations emphasize that both the Lumut and Endau sediments have a well-defined granular skeleton which is more stable in nature. On the other hand, the northern sediments of fine and clayy nature are highly compressible and they need to undergo rigorous chemical treatment to obtain the structural stability demanded by engineering use.

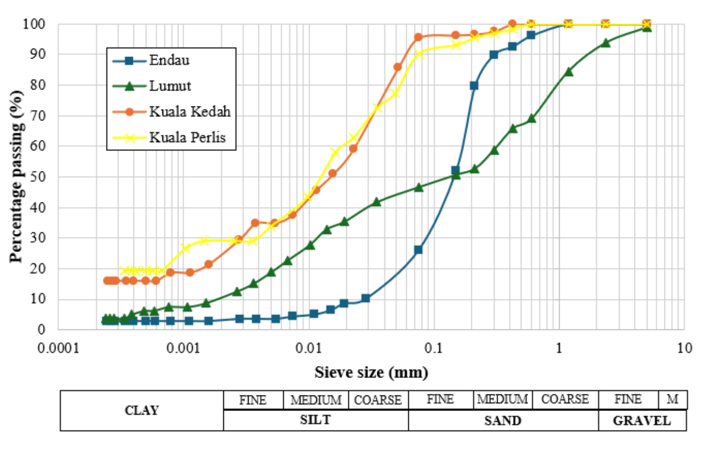

Fig.3 Particle size ditribution (PSD) curves for regional DMS samples.

3.2 Consistency Limits and Specific Gravity

The consistency indices play a critical role in establishing the reaction of the soil to the presence of moisture and determining its engineering capability because high plasticity soils are also highly correlated with a high compressibility. With the highest consistency values, the KK and KP sample had Liquid Limits (LL) of 55.96% and 54.87% respectively. These northern sediments are either considered to be high-plasticity silts or organic clays according to the Casagrande classification[4]. These high values give a microscopic explanation of the high initial void ratios (e_0) and high settlement potential registered during the baseline tests of consolidation. The Endau sample on the other hand had a very low Plasticity Index of 2.94 which points to an inter-granular friction between the sand particles as the main source of behavior. The reported Gs results showed mineralogical differences; the lowest Gs of 2.45 was recorded in KK implying the existence of organic matter that can disrupt the cement hydration.

3.3 Natural Moisture content vs. Compaction Benchmarks

One critical observation in this stage was the huge difference between the Natural Moisture Content (w_n) and the Optimum Moisture Content (OMC) of compaction tests[12] . In the case of the northern locations such as Kuala Perlis, the wn reads almost six times its OMC 33.0 percent which demonstrates that the raw Malaysian DMS is in semi-fluid slurry form. This reason of high moisture retention is attributed to the microstructural arrangement that is observed in Fig 4. Microscopic observations of the untreated northern clays using Scanning Electron Microscopy (SEM) indicates that the materials are open and flocculated into a house of cards-like configuration with considerable inter-particle voids which hold water. This base confirms that mechanical compaction cannot be used in isolation to overcome this over excess moisture barrier and that chemical stabilization is required to convert geo-waste into a useful engineered backfill.

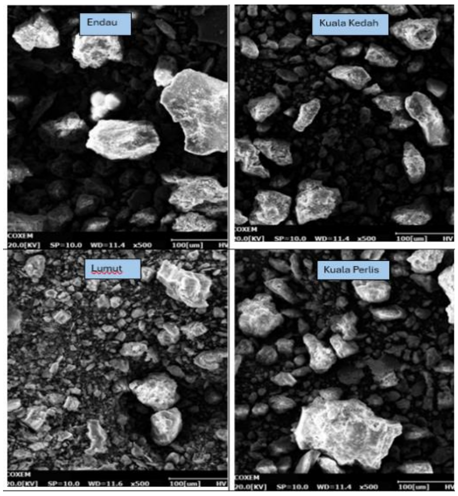

Fig.4 SEM Micrographs of untreated DMS samples at 500x magnifications

3.4 Summary of Physical Characteristics

The general physical characterization of the coastal sediments located in the region (DMS) provides a steep geotechnical barrier between the northern and southern/western areas of the coast of Peninsular Malaysia. The main precondition of this regional variability is the environmental energy of the dredging locations that has a great influence on the organization of the particles and mineralogical structure of the "geo-waste" material. Northern sediments of Kuala Kedah 96.64% fines and Kuala Perlis 90.18% fines are unanimously fine-grained resulting in a high plasticity and water-holding capacity. Lumut 53.35% sand and Endau 74% sand are much coarser in contrast and exhibit more stable granular behavior. The results are consistent with site-specific characterizations that indicate that properties of marine sediments differ radically with dredging source. One of the most important findings is the vast difference in moisture conditions; this is because natural moisture content (w_n) of places in the north such as Kuala Perlis is almost six times more than the Optimum Moisture Content (OMC), which means that raw DMS is present in the form of a semi-fluid slurry. The semi fluid condition renders mechanical compaction solely physically incapable of structural stability [7]. Microstructural studies by SEM and XRD define that the extreme compressibility of northern clays is due to an open, flocculated house of cards structure with large inter-particle pore [4]. As a result, the southern granular sediments are more naturally stable whereas the problematic northern clays need intensified chemical treatment by using binders such as 5% OPC or 4% PMC in order to form a solid engineered skeleton that can be used as a structural backfill [2,10].

Table 3: Consolidated Summary of Physical and Compaction Properties

Sampling Location	**Soil Type**	**Liquid Limit (LL) (%)**	**Plasticity Index (Ip)**	**Natural Moisture (wn)(%)**	**MDD**
Kuala Kedah	High Plasticity Silt/Clay	55.96	13.04	127.96	1.02
Kuala Perlis	High Plasticity Marine Clay	54.87	9.79	180.89	0.92
Lumut	Silty Sand	43.32	5.12	28.67	1.08
Endau	Sandy Clay/Clayey Sand	28.69	2.94	35.20	1.23

4. One-Dimensional Consolidation Performance

The mechanical evaluation of stabilized Dredged Marine Soils (DMS) was conducted using the one-dimensional oedometer test to derive the Compression Index (Cc), Pre-consolidation Pressure (σ'p), and Coefficient of Consolidation (Cv). These parameters are critical for verifying whether treated geo-waste can fulfill the strict settlement requirements prescribed by the Public Works Department (JKR) Malaysia for engineered backfills.

4.1 Compressibility Characteristics and Structural Rigidity

The relationship between the void ratio (e) and vertical effective stress (log σ') reveals a sharp geotechnical divergence between untreated and stabilized states. Untreated northern clays from Kuala Kedah (KK) and Kuala Perlis (KP) exhibited extreme compressibility with Cc values of 0.47 and 0.37, respectively, indicating an inherently loose soil structure. Stabilization with 5% Ordinary Portland Cement (OPC) successfully reduced the Cc of KK to 0.21, a 55% improvement [6]. However, the most significant breakthrough was achieved with the 4% Polymer Modified Cement (PMC) treatment, which reduced the Cc of KK to a near-negligible 0.003. This represents a 99.3% reduction in compressibility, transforming soft clay into a virtually incompressible rigid engineered skeleton.

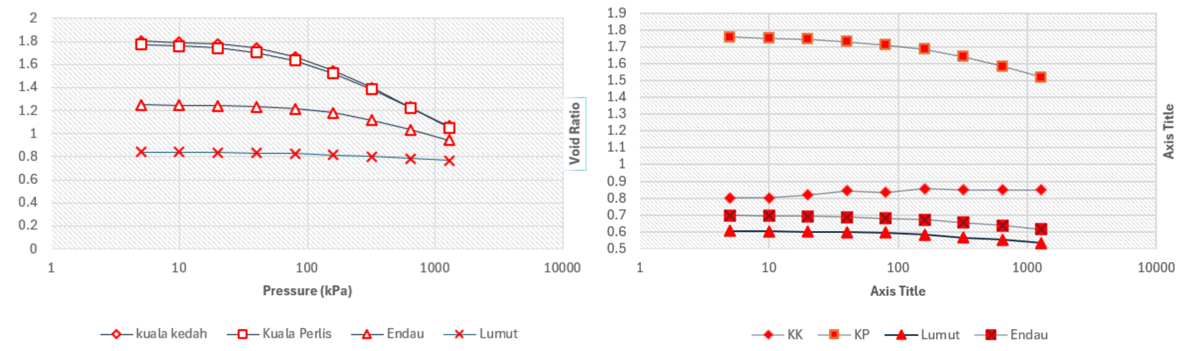

Fig.5 Comparative e-log p consolidation curves: (a) Untreated regional DMS; (b) 4% PMC stabilized DMS

4.2 Drainage Effieciency and the infinite Consolidation Status

The main interest of this research is the results of the oedometer test i.e. the rate of pore water dissipation that determines the total time of settlement. The Coefficient of Consolidation (Cv) is a regulative factor that oversees the efficacy of hydraulic conductivity, as well as the rate of losses of pore water dissipation9[2]. Findings indicate that untreated samples in the northern region had slow drainage with an average Cv of 67.0 m^2/year, which is a cause of serious threats of long-time subsidence. This sluggish drainage characteristic is characteristic of high-plasticity marine clays that in many cases need external soil enhancement, like Prefabricated Vertical Drains (PVDs) to speed up the consolidation process [4].

Even though the addition of 5% OPC initially increased the drainage, it ultimately caused a clogging effect when subjected to heavy vertical loads with the Cv values dropping as low as 9.65 m^2/year. This happens when hydration products (i.e. Calcium-Silicate-Hydrate (C-S-H) gels) block physically the micro-pores and occupy the unfilled spaces between the soil particles6. This practically entraps pore water in the soil matrix and slows down the rate of consolidation which is major engineering issue because it prolongs primary consolidation period compared to standard project schedules.

On the other hand, 4% PMC stabilization ensured constant consolidation rates in all the samples (regional samples) with an average of 850.00 m^2/year of consolidation. This breakthrough act is credited to a dual bonding process in which the polymer structure binds the clay particles into stable non-collapsible flocs. These flocs form large continuous drainage channels and spatial network channels and structure that is open even to high vertical stress. This enables it to settle practically within seconds in the construction stage and proves that PMC-treated DMS is effective in removing the use of PVDs because primary settlement occurs within days, not years.

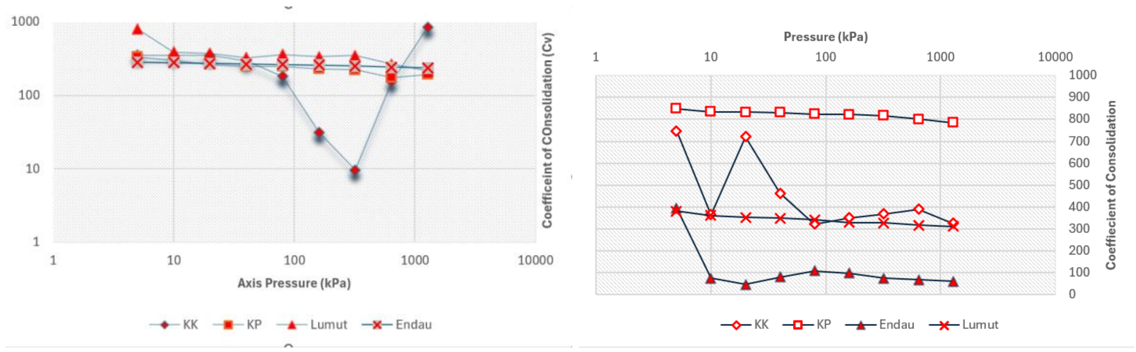

Fig.6 Variation of Cv against axis pressure: (a) Pore-clogging observed in 5% OPC; (b) "infinite" drainage efficiency in 4% PMC

4.3 Comparative Summary of Stabilization Effiency

A technical synthesis of the results confirms that 4% PMC is the optimized solution for repurposing Malaysian geo-waste[5][9]. While 5% OPC serves as a functional baseline, only PMC treatment successfully eliminates the dual failure risks of excessive settlement and hydraulic bottlenecks. As summarized in Table 4, PMC-treated DMS comfortably meets JKR allowable settlement limits by providing both high structural stiffness and superior drainage.

Table 4: Summary of Mechanical Improvement across all Soil States

Sampling Location	State	Fines (%)	Cc (Avg)	cv (Avg) [m^2/yr]	JKR Compliance (Settlement)
Kuala Kedah	Untreated	96.64	0.470	67.0	Fail
	5% OPC	-	0.210	45.30*	Marginal
	4% PMC	-	0.003	849.21	Pass (High)
Kuala Perlis	Untreated	91.56	0.370	636.0	Fail
	5% OPC	-	0.240	442.15	Pass
	4% PMC	-	0.150	850.00	Pass (High)
Lumut	Untreated	46.65	0.060	634.0	Pass
	4% PMC	-	0.056	850.00	Pass (High)

*Note: 5% OPC in KK exhibited a "clogging effect" where Cv dropped to 9.65 m^2/yr at high pressures.

5. Engineering Implications and Conclusion

The definition of stabilization in the large-scale engineering practice involves a strict test of stabilization results, under the simulated conditions of the field. This part provides a summary of the experimental findings in order to illustrate how problematic regional geo-waste in places like Kuala Kedah and Kuala Perlis can be effectively re-engineered to make a high-performance backfill. Using particle size distributions and the novel compaction resistivity of the polymer-cement co-matrix and its unlimited draining ability, the current research provides a technically viable and sustainable way of achieving coastal reclamation in Malaysia. The optimized 4% PMC treatment is able to remove the critical failures noted in untreated soils and OPC-stabilized soils namely: excessive long-term settlement and inhibitory clogging effect.

5.1 Performance Simulations of Reclamation Layer

To illustrate the use of the findings, a simulation study on the performance of a 5.0-meter-thick layer of reclamation layer was performed using Kuala Kedah DMS under a typical embankment loading of 150 kPa. The natural, untreated soil has calculated total settlement of more than 1.2 meters and a low Cv of 67.0 m^2/year and it takes over 3 years to achieve 90 percent primary consolidation (t_{90}) [6]. These conditions usually require costly and lengthy processes of soil improvement, including Prefabricated Vertical Drains (PVDs), which can be much more costly in capital and holding time of the project [7].Instead, the DMS with 4 per cent PMC will reduce settlement to a controllable 7.5 mm with total consolidation in less than 10 days because of an unlimited Cv of 849.21 m^2/yr. This will ensure that settlement is made virtually at the loading stage and the material will not be subjected to the JKR acceptable limit of less than 100 mm[9] settlement. PMC method is an instant solution that does not require such secondary drainage systems as opposed to traditional PVD applications that may take a few months at a cost of about RM 5.00 to RM 10.00 per linear meter to consolidate.

Table 5: Comparative Performace of Reclamation Methods

Method	Total Settlement (mm)	Time to t90	Cost / Complexity
Untreated DMS	> 1200 mm	> 3 Years	High Holding Costs
DMS + PVDs	~1000 mm	6–9 Months	High Material/Labor Cost
DMS + 4% PMC	7.5 mm	< 10 Days	Low (Single Process)

5.2 Conclusions of Research Findings

The extensive laboratory research is a conclusive statement that 4 percent Polymer Modified Cement (PMC) is the most effective stabilization binder in transforming the problematic Malaysian Dredged Marine Soils (DMS) into effective engineered backfill. The study reveals that incorporation of a polymer phase in a conventional cementitious system removes structural and hydraulic limitations that are imposed by the northern regional clays. This two-action bonding measure delivered a reduction in compressibility of 99.3 percent in Kuala Kedah samples which yielded an almost rigid skeleton with Compression Index (Cc) of 0.003. In addition, PMC treatment guarantees great hydraulic efficiency, wherein fine particles are aggregated into stable flocs that offer large drainage channels, which keeps the Cv values high even with excessive loads on the vertical axis. The paper is successful in converting an environmental waste stream into a construction resource that is sustainable, which meets SDG 9 and SDG 12 [13].

5.3 Recommendation for Future Research

To implement these findings in the industry, it is proposed that there are several research directions. The study should be conducted in a 50-year study period to identify the retention and leaching properties of the polymer-modified matrix during long-term (when subjected to high salinity marine environment) in the long-term (long-term) service life. Another process that should be carried out is curing optimization under submerged conditions to mimic the deep-sea reclamation, in which deep-sea conditions cannot be dried using the atmosphere drying. Besides this, pilot-scale field tests are proposed to verify the "Infinite" rate of consolidation as applied to the world variables which include the non-uniform mixing and complex boundaries of drainage. Finally, the advanced microstructural mapping should be attained by way of SEM and EDX in order to offer a certain scientific impact on the distribution of polymer filaments and hydration gels that will offer a conclusive scientific basis of the mechanical advances which have been observed.

Acknowledgement

The authors confirm contribution to the paper as follows: study conception and design: Muhammad Affan Daniel Bin Nor Rizan, Chan Chee Ming; data collection: Muhammad Affan Daniel Bin Nor Rizan; analysis and interpretation of results: Muhammad Affan Daniel Bin Nor Rizan, Chan Chee Ming; draft manuscript preparation: Muhammad Affan Daniel Bin Nor Rizan . All authors reviewed the results and approved the final version of the manuscript.

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