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Evaluation of climate change on the collapse potential of unsaturated cement-treated laterite soil for disaster risk reduction

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Abstract. Extreme weather events and intense rainfall may alter the climate, which would probably affect the geotechnical constructions such as unsaturated embankments. Basically, soil moisture content determines the strength of the unsaturated soil, with wetter soils often being weaker. Although it has been proved that unsaturated condition substantially impacts the shear strength and volumetric behaviour of soil, its implications are rarely investigated or taken into account in the design. As a result, changes in temperature and rainfall loads will have an influence on geotechnical constructions and develop long-term seasonal deformations that might severely jeopardize safety and maintenance. Therefore, it is crucial to assess the effects of the climate on soil behaviour for each location through adequate geotechnical laboratory tests. Johor, Malaysia has a large area and abundant tropical soils. Hence, this study aimed to elucidate the influence of climate change on soil behaviour in the tropical regions of Johor. To impose Malaysia's climate, a series of modified suction-controlled oedometer tests are conducted under different matric suctions. The outcomes revealed that the low and high matric suction has significantly impacted the untreated and cement-treated soil. However, the great reduction of soil settlement is mostly from the coupling effect of saturation and stabiliser.

1 Introduction

In Malaysia, the effects of climatic change are noticeable. Heatwaves are predicted to happen more frequently every year as temperatures increase. Precipitation changes could cause extensive floods and droughts in various local areas. Some coastal regions could get inundated as sea levels rise. These consequences are anticipated to have a wide range of disaster risks, socioeconomic implications, escalating inequality, and aggravating already-existing environmental issues. Due to the substantial consumption of coal and natural gas, Malaysia itself produces pollutants. However, the usage of hydropower has increased in the twenty-first century, and research is being done on other possible energy sources, including solar energy and biomass [1]. It is anticipated that the currently existing environmental pressures (for instance, deforestation) on natural resources would exacerbate. At present, USD 1.3 billion in damages have been brought on by natural catastrophes, primarily from flooding [2].

The alternate weather (rainy and hot seasons) in Malaysia alters the existing environmental conditions. The soil's moisture content is one of the most crucial elements in the natural environment. Any change in a region's moisture level has an impact on the soil conditions. So, in its normal condition, the soil above the ground water table is considered as partially saturated [3]. In these situations, soil is referred to as semi-saturated or being called as "unsaturated." Since such soil layers are more often exposed to atmospheric, environmental, and physical impacts, their moisture content is more susceptible to fluctuation. Most tropical regions, including Malaysia, are affected by this matter. Such circumstances may result in severe, irreparable damage to the foundations of buildings and other structures constructed on such soils of the above-ground water table, consequently leading to natural disasters.

Many geotechnical issues are caused by the existence of partially saturated soil zones, in which the voids between soil particles are filled with a mixture of water and air. In fact, these zones are frequently neglected, and it is deemed that the soil is fully saturated or fully dry. This is because the standard theory of soil mechanics considers soil as either entirely saturated or completely dry. Indeed, cohesive saturated soil possesses a lower strength than unsaturated soil, depending on the loading conditions [4]. Thus, if saturated conditions are the only ones taken into account while designing a structure, then overdesign issues and exorbitant costs could emerge.

In general, unsaturated soils' constitutive behaviour is profoundly affected by variations in soil suction that have been related to changes in moisture content. Therefore, while solving geotechnical engineering problems, the impacts of suction change on the hydro-mechanical behaviour of soils, such as deformation, shear strength,

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and volume change behaviour (swelling or collapse), are of particular concern. Currently, two distinct theories describe the mechanical behaviour of unsaturated soils. First, Bishop created the first theory based on the effective stress principle, called the effective stress technique for unsaturated soil [5]. Fredlund, on the other hand, asserted that two independent variables, matric suction, and net normal stress, are required to completely define the behaviour of unsaturated soil [6, 7]

In 1989, Fredlund advocated that two independent stress state variables, net normal stress ($\sigma - u_a$) and matric suction ($u_a - u_w$), should be used to characterize the constitutive behaviour of unsaturated soils (where σ is total stress, u_a is pore air pressure, and u_w is pore water pressure) [8]. Similarly, Fredlund and Rahardjo [6, 7] proposed using net normal stress and matric suction to characterize the mechanical behaviour of unsaturated soils. Although this stress state variables technique has received a lot of attention in the research, it has not been used extensively in actual practice. For determination of the material characteristics, the technique requires significant and prolonged laboratory testing, especially for fine-grained materials where the material coefficient of permeability is relatively low. Besides, the laboratory devices employed for the unsaturated soil are typically complex and costly, and the skill level needed to determine the unsaturated parameters is frequently above average for many geotechnical engineering laboratories. Hence, this article examines the impact of the matric suction stress state variable on the unsaturated soil settlement and collapse potential.

2 Materials

The samples of disturbed laterite soil are obtained from an open space near the P16 Block, Faculty of Electrical Engineering, University of Technology (UTM) Johor, Malaysia, as shown in Figure 1. The soil specimens are collected by backhoe digging work one meter below the ground's surface. Before the soil specimens are taken to the laboratory to be dried for 3 days' oven-dried and 3 days' 60°C oven-dried, all the topsoil and humus are removed. The low oven-dried temperature is to prevent temperature influences on the properties of the soil [9–11].

Fig. 1. Soil specimen's location.

Meanwhile, Ordinary Portland Cement (OPC) is employed as a stabiliser for soil strength enhancement to stabilise the laterite soil. The YTL company manufactures this OPC, which is classified as CEM I 42.5N / 52.5N and complies with MS EN 197-2:2014 requirements. In contrast to other cement categories, OPC CEM I is selected due to its great clinker percentage of 95–100%, which implies greater strength [12]. This higher percentage of clinker might speed up the cement hydration rate, enabling an immediate strength gain [13].

3 Methodology

3.1 Physical tests and soil classification

Soil classification and geotechnical properties tests are performed based on preferred standards, as listed in Table 1.

Table 1. Preferred standard for each laboratory test.

Tests		Standards
Water content		BS EN ISO 17892-1:2014
Particle density		BS EN ISO 17892-3:2015
Particle size distribution	Wet sieve	BS EN ISO 17892-4:2016
	Particle analyser	ISO:13320 (2009)
Atterberg limit		BS EN ISO 17892-12:2018
Compaction		BS 1377-4:1990
Unconfined compressive strength (UCS)		BS EN ISO 17892-7:2017
Modified suction-controlled oedometer		BS EN ISO 17892-5:2017

3.2 Unconfined compression test

The unconfined compressive strength tests were performed on specimens of 38 x 76 mm dimensions. These unconfined compressive strength tests made it possible to compare untreated and cement-treated laterite specimens' unconfined compression strength (UCS). These tests are performed on cured specimens that had been prepared based on the specified OMC and MDD values. In order to determine the UCS, the prepared specimens are immediately wrapped in plastic film, placed in a plastic container, and stored in a humidity chamber for various curing periods (0, 3, 7, 14, and 28 days). The reason for selecting varieties' curing periods is to fully understand how strength develops over time and the impact of short-term strength characteristics of the cement-treated soil. This is because cement offers initial, short-term strength as a result of the first hydration process.

3.3 Modified suction-controlled oedometer

Meanwhile, for the modified suction-controlled oedometer test, the specimens involved are only untreated laterite, and 6% cement-treated laterite at 7 days of curing, which is selected based on Malaysia Public Work Department standards. To execute the soil settlement and collapse potential analysis, a one-dimensional compression test using a framework of modified suction-controlled oedometer is conducted on unsaturated untreated and cement-treated soil under both saturated and unsaturated conditions, with the application of the axis translation technique to control the suction (weather conditions). In order to analyse collapse and volume change in an unsaturated state, the suction-control oedometer test is essential. It is well acknowledged that the outcomes of wetting and drying analyses performed on unstable soils in the laboratory by adopting the matric suction give reliable experimental data to evaluate the soil collapse behavior [14–16]. Before the soil settlement analysis, the UCS test is conducted first to identify the adequate optimum cement dosage and optimum curing period required for soil stabilisation process. After that, the modified suction-controlled oedometer test is operated under 3 stages: zero matric suction, constant matric suction test in wetting conditions, and constant matric suction test in drying conditions.

For the constant matric suction test in the drying state, the required suction (400 kPa) is kept constant during the test while the vertical net stress (loading) is raised up to 9000 kPa. After assembling the chamber, the designed suction is first applied to the sample under the seating load. Once reaching the desired suction, a step loading is applied to the chamber. After the chamber has been assembled, the desired suction is applied to the specimen. A step loading is then applied to the system after the suction equalisation process has been achieved. Meanwhile, the procedure for performing the wetting tests is similar to that of the drying tests, where the desired suction is 20 kPa.

Figure 2 illustrates the assembled system of the modified suction-controlled oedometer test. Three separate devices have been utilised to regulate the vertical net stress, air pressure, and water pressure in conducting a modified suction-controlled oedometer test. A loading rod attached to a loading frame is used to apply the vertical net stress. A linear variable displacement transducer (LVDT) is attached to record the vertical displacement on the top of the loading frame. Next, a GDS pneumatic controller is employed to regulate air pressure. In addition, the top of the porous stone is also subjected to air pressure via a valve that passes the perforated loading platen. A 15-bar High Air Entry Value (HAEV) ceramic disk is embedded into the pedestal using a unique epoxy resin. The ceramic disk serves as an interface between the water in the pressure controller and the water in the soil pores, preventing free air passage into the water measurement system. Meanwhile, the water pressure is regulated by using a GDS Advance Pressure/Volume Controller (ADVDPC). Throughout the test, a GDS data logger connected to a computer automatically documented changes in water volume, vertical displacements, air pressure, and water pressure.

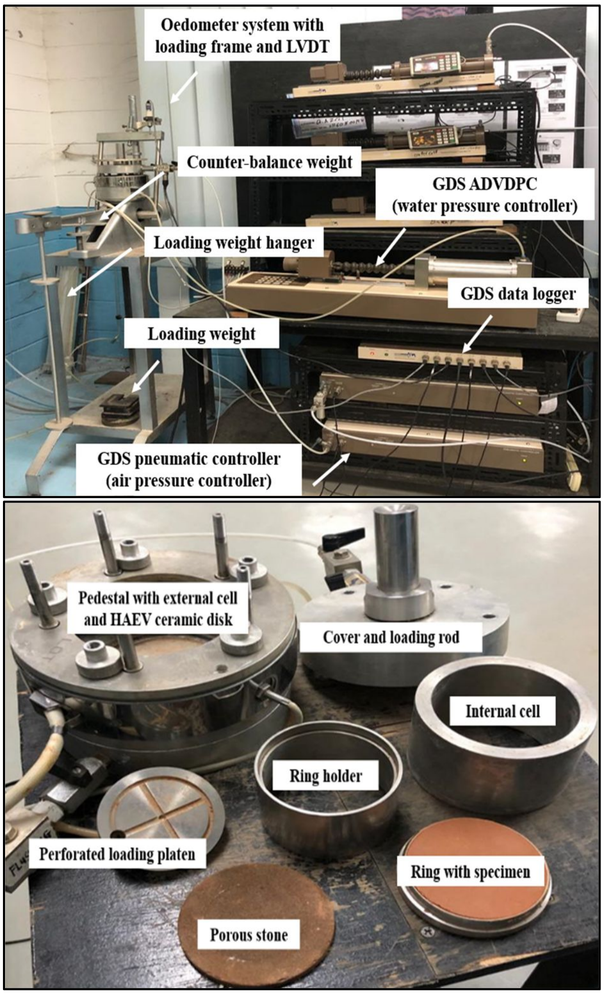

Fig. 2. Assembled system of the modified suction-controlled oedometer.

4 Results and discussions

4.1 Physical test and soil classification

As presented in Table 2, [17] has outlined the particular criteria that distinguish between laterite soil, lateritic soil, and non-lateritic soil. Hence, mineralogy analysis of X-ray fluorescence in Table 3 indicated that the representative soil specimen is categorized as Laterite soil.

Table 2. Classification of laterite, lateritic, and non-lateritic soil [17].

Ratio of SiO_2 / Al_2O_3	Soil type
Less than 1.33	Laterite soil
1.33 to 2.00	Lateritic coil
More than 2.00	Non-lateritic soil

Table 3. X-ray Fluorescence analysis for laterite.

Elements	Laterite (%)	Ratio of SiO_2 / Al_2O_3	Soil type
Al_2O_3	41.00	0.85	Laterite
SiO_2	35.00		

Meanwhile, based on the soil classification test results in Table 4, it is revealed that the laterite soil is sandy silt of high plasticity, MV. Since the liquid limit is less than 80% and the plasticity index is less than 55%, the laterite soil is deemed suitable for construction work [18]. Hence, the laterite soil may proceed for the next laboratory testing programs.

Table 4. Results from various soil testing for laterite and cement-treated laterite.

Tests results		Values
Natural water content (%)		40
Liquid limit (%)		70
Plastic limit (%)		42
Plasticity index (%)		28
Gravel (%)		13
Sand (%)		18
Silt (%)		61
Clay (%)		8
Particle density (g/cm^3)		2.74
Optimum moisture content (%)	Laterite	28
	3% cement-treated	27
	6% cement-treated	28
	9% cement-treated	30
	12% cement-treated	31
Maximum dry density (g/cm^3)	Laterite	1.39
	3% cement-treated	1.47
	6% cement-treated	1.43
	9% cement-treated	1.40
	12% cement-treated	1.38
BSCS classification		MV (very high plasticity sandy SILT)

4.2 Unconfined compression test

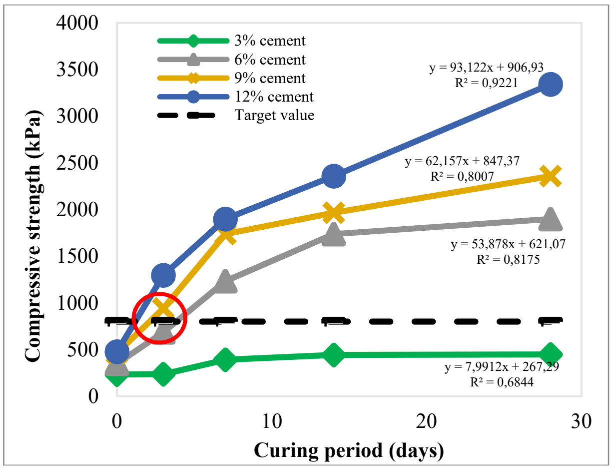

Fig. 3. Graph of compressive strength versus curing period for all specimens.

The influences of cement as stabiliser can be seen clearly on the UCS of fine-grained laterite soil, as depicted in Figure 3. Overall, it is observed that UCS keeps increasing with increases in cement dosages and curing period, especially for 9% and 12% cement contents. This increase in strength is caused by the laterite soil's treatment, which reflected an improvement in the soil's bearing capacity. This enhancement of bearing capacity is firstly due to the hydration of the cement, which stiffens the treated laterite [19–24]. Second, the cement addition to the laterite has produced excessive amounts of cemented products, specifically CSH, CAH, and CASH, which aid in the strength and resistance gains [25].

The most important thing is that 6% cement at 7 days' strength is found to be the optimum stabiliser dosage in low-volume road subgrade construction, and the obtained values are 1233 kPa (as circled in the graph). Thus, the strength value exceeds the strength target value (800 kPa), as outlined by the Malaysia Public Work Department [26].

Hence, for the modified suction-controlled oedometer test, only 6% cement-treated laterite will be conducted and analysed.

4.3 Modified suction-controlled oedometer

One-dimensional consolidation tests have been carried out under suctions in both the drying and wetting conditions since unsaturated soil behavior in drying conditions differs from that in wetting conditions, which is known as the hysteresis phenomenon [6]. The continual suction test can be performed in either a drying state (increases/high suction) or a wetting state (decreases/low suction). The modified suction-controlled oedometer is employed as well with the axis translation approach to execute and control suction.

Figure 4 illustrates the obtained compression curves for specimens in both wetting and drying state. It can be seen that at the higher suction (drying condition), cement lead to more cement-laterite aggregates/lumps, which creates more spaces between inter-aggregates of soil, thus, the cement-treated laterite at 400 kPa sustained higher void ratio values compared to the specimen at 20 kPa. The outcome agrees with [27, 28]. This describes how the coupling effect of suction and stabiliser altered the soil's natural structure and capacity to absorb water. However, when the applied stress escalated, the soil porosity decreased as a result of the progressive breakage of inter-granular bonding which caused by the loading [29].

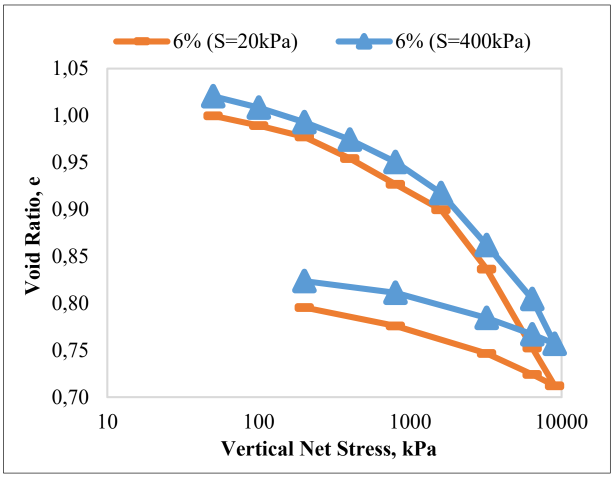

Fig. 4. Graph of compression curves (vertical net stress versus void ratio) for 6% cement-treated sprecimens at both wetting and drying conditions.

Additionally, it has been shown that the cement stabiliser has an additional effect on the change in soil volume than the suction. This is due to the fact that, as shown in Table 5, the compression index, C_c, for 6% cement-treated at 20 kPa suction is 0.245, meanwhile, the C_c for 6% cement-treated at 400 kPa suction is much more lower, giving the values of 0.234. Therefore, the soil structure seems to have become more rigid under the greater suction (drying condition) compared to the lower suction (wetting condition), which helps the soil withstand tremendous overburden pressure. Therefore, the soil structure is more favorable under drying state (400 kPa suction) than under a wetting state (20 kPa suction). The same goes for the recompression index, C_r results, where the difference of C_r quite significant between specimens in low and high suctions.

Table 5. Results for compressibility parameters (C_c and C_r) for 6% cement-treated laterite at both wetting and drying conditions.

Testing parameters	Conditions of 6% cement-treated laterite	
	20 kPa (wetting)	**400 kPa (drying)**
Compression index, Cc	0.245	0.234
Recompression index, Cr	0.050	0.040

Besides, as the degree of cementation exist in the soil, the effect of suction / capillary forces on the inter-granular bonding also can be seen. This outcome is in line with earlier findings by [30–32]. It is clearly depicted on **Fig. 5**, where the preconsolidation pressure, P_c of 6% cement-treated laterite is 1800 kPa at 20 kPa suction and 2200 kPa at 400 kPa suction. These events occurred firstly due to the hydration reactions, aggregation effects, particle rearrangement, and pozzolanic reactions that occurred in the presence of cement in the soil and water [22]. Second, it has been discovered that the suction functioned by causing the soil stiffer as the loading developed.

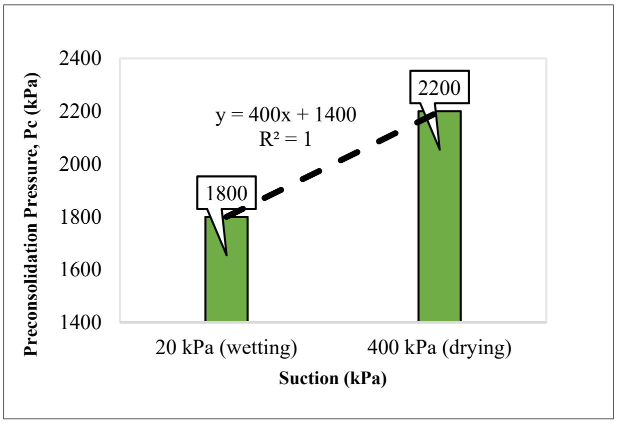

Fig. 5. Graph of preconsolidation pressure for 6% cement-treated laterite at both wetting and drying conditions.

On the other hand, In 1994, [33] introduced the collapse potential severity to signify the problem severity of the soil. The collapse potential (CP) has been calculated and depicted in Figure 6 by referring to the proposed equation by Fookes as tabulated in Table 6. The CP equation is stated below:

$$CP\ (\%) = (\Delta e / 1 + e_o) \times 100 \qquad (1)$$

where:
Δe = change of void ratio (e_i- e_f)
e_o = initial void ratio
e_i = void ratio for unsaturated specimen
e_f = void ratio for saturated specimen

Further, it can be seen that the CP for 6% cement-treated laterite soil at 20 kPa suction is much higher compared to the 6% cement-treated laterite soil at 400 kPa suction. Furthermore, the CP for cement-treated specimens for both conditions still within the range of 0-1 %, indicating the soil is non-problematic. Therefore, adding cement as stabiliser has a high potential to reduce the collapse severity, which may reduce the catastrophe risk associated with road construction in the specified region.

Table 6. Severity of collapse potential [33].

Collapse potential (%)	Severity of problem
0 – 1	No problem
1 – 5	Moderate trouble
5 – 10	Trouble
10 – 20	Severe trouble
> 20	Very severe trouble

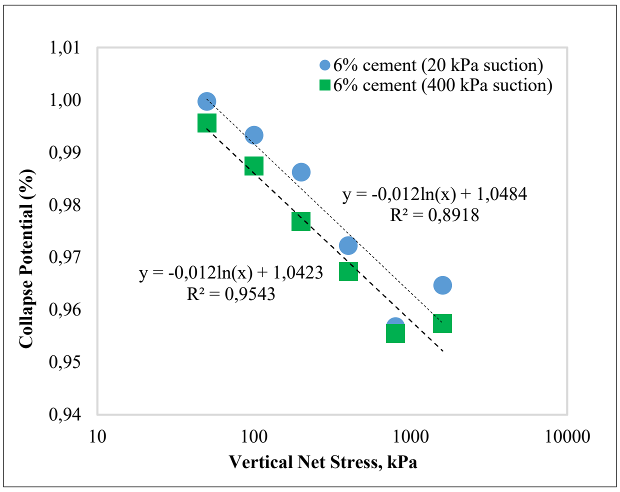

Fig. 6. Graph of collapse potential versus vertical net stress for all specimens at desired suctions.

5 Conclusion

There are several main conclusions have been drawn from the research paper:

1. The laterite soil strength properties can be improved and achieve 800 kPa strength with the application of CEM I/42.5 N cement as a stabilising agent, allowing the potential of utilising this laterite soil for road subgrade construction, as per stated by Malaysia Public Work Department.
2. To achieve the required mechanical properties and reduce the disaster risk of road subgrade, 6% cement dosages are sufficient.
3. High void ratio is clearly apparent in high suction (drying condition) compared to the specimens in low suction (wetting condition).

4. The cement-treated laterite soil have induced higher preconsolidation pressure at high suction (drying condition) compared to the specimens in low suction (wetting condition).
5. The soil severity of problem for 6% cement-treated laterite signified as 'no problem', where the collapse potential is in range 0-1 %.
6. The strength and stability of 6% cement-treated soils are much better during the dry season (drying condition) compared to the rainfall season (wetting condition).

Overall, this paper has outlined the differences in unsaturated cement-treated laterite between low and high suctions in terms of soil compressibility. Therefore, these obtained results may be proposed as a guideline for further researchers so that the issues of overdesign or underdesign may be avoided.

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