

LOAD VERSUS SETTLEMENT BEHAVIOR OF SOFT CLAY REINFORCED WITH CEMENT STABILIZED RECYCLED ASPHALT PAVEMENT-LATERITIC SOIL COLUMN

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Abstract

In this paper, the performance of cement stabilized recycled asphalt pavement (RAP)-lateritic soil column inclusion in soft clay was investigated via a physical model. The load-settlement response and bearing capacity of the composite ground were studied at various cement contents (0%, 1%, and 3%) and at a 30% RAP replacement ratio. The soft clay was consolidated in the PVC mold with a diameter of 150 mm and 300 mm high, while the stabilized RAP-lateritic soil column with a diameter of 50 mm was used as a column at the center of the soft clay. The results showed that the bearing capacity of the composite ground significantly increased with the increased shear strength of the column. The purposed bearing capacity equation derived from the unconfined compressive strength of the column and the undrained shear strength of soft clay was found to predict the bearing capacity of the composite ground satisfactorily.

Keywords: Cement stabilization; Ground improvement; Lateritic soil; Recycled asphalt pavement; Stone column

Introduction

Compressible soil with low bearing capacity is undesired for infrastructure construction projects. The deep foundation is generally employed to carry load from the superstructure and transfer to hard stratum. For low to medium heavy superstructures, stone column or granular pile foundation is an alternative ground improvement technique. The soft clay layers improved by the stone column can carry a more vertical load and reduce the consolidation

settlement and time. The installation of the stone column is more economical than the pile foundation for low to medium-heavy superstructures. Typically, the stone column technique can be executed by drilling the hole, then filling the aggregate, and densifying vertically to form the columnar. The soil surrounding the compacted column functions as a confinement against the aggregate movement. The stone column's aggregate

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is commonly made of quarry stone which is strong and clean with a high friction angle.

With the conservation of inadequate natural resources, engineers and researchers have been looking for alternative materials instead of quarry stone for stone column construction. Tons of waste materials generated from construction and demolition (C&D) annually increased. These waste materials include those such as wood, crushed concrete, crushed brick, glass, and steel slag. Without the suite management, a large volume of these wastes was disposed of to landfills.

Some kinds of C&D may contain toxicity and then affect the soil and groundwater environment in the short and long terms (Cabrera *et al.*, 2019). Many researchers evaluated the feasibility of various types of C&D as alternative construction materials. With the suitable improvement technique, the recycled materials can be used as alternative construction material (Hoy *et al.*, 2023; Nhieu *et al.*, 2023). Using C&D as sustainable construction materials saves the large extraction of unrenewable virgin resources and is cost-effective.

Regarding stone columns, many types of C&D materials or industry activities were evaluated for the possibility of replacing the traditional stone column aggregate (Zukri and Nazir, 2018). The various type of C&D materials and industrial materials i.e. fly ash aggregate, tire ship, crushed concrete, railway ballast, and crushed waste glass, were evaluated for the possible usage as stone column aggregate (Serridge, 2004; Ayothiraman and Soumya, 2015; Alkhorshid *et al.*, 2019; Kazmi *et al.*, 2023). The large-scale model of soft ground reinforced by compacted stone columns was investigated under both end-bearing and floating installations. These studies revealed that recycled aggregate is feasible as an alternative aggregate filler.

Recycled asphalt pavement (RAP) is waste debris from asphalt pavement rehabilitation. The properties of RAP are similar to those of original asphalt pavement except for the rheological properties of asphalt binder course by UV exposure and various traffic impacts. RAP may be unsuitably reused for embankment and fill application unless being the treated (i.e., scaping, mixing with aggregate, temperature, and confinement) (Dager *et al.*, 2023). With its well gradation and high friction angle, several engineers and researchers have evaluated the use of RAP in many civil engineering applications, especially in highway work. RAP mixing with aggregate was found to provide to satisfy the result. The RAP-aggregate blends can meet the strength requirement for road-based materials (Suebsuk *et al.*, 2014; Cosentino *et al.*, 2003). However, the allowable proportion of

RAP were reused in construction projects is still limited (Suksan and Horpibulsuk, 2022).

The ground improvement technique using stone column is typically acceptable for soft to medium clay (undrained shear strength, $S_u > 15$ kPa) due to the sufficient confinement to against the movement of cohesionless stone column aggregate. The interlocking effect enhancing the strength of stone column aggregate is ineffective when installing in very soft clay. Previous studies were conducted to investigate the feasibility with various methods to extend the limitation of stone column installation (Sushovan *et al.*, 2016; Golait and Padade, 2017; Lin *et al.*, 2023).

Therefore, this study aims to ascertain the cement stabilized recycled asphalt pavement (RAP) - lateritic soil blends as stone columns. The clay model was set up and the end-bearing stone column was installed at the center to perform the bearing capacity test of the composite ground. With the proper RAP-lateritic soil mixture, the stone column aggregate comprised of the lateritic soil which was replaced by RAP at 30% by dry weight. The ordinary Portland cement was mixed with the lateritic soil and RAP blend at 1% and 3% by dry weight of the blend. The load-settlement response of the composite ground model was measured and analyzed to develop a predictive equation for bearing capacity of composite ground. This developed equation is significant for the geotechnical design of earthen structures, which is the novelty of this research. The outcome of this study will promote the usage of RAP and lateritic soil as aggregate in stabilized columns in a sustainable manner.

Materials and Methods

The clay sample was collected from a construction site in Nakhon Ratchasima province, Thailand, at a depth of about 4-5 m below ground level. Its liquid and plastic limits were 37% and 28%, respectively. The lateritic soil sample was sourced from a borrow site in Nakhon Ratchasima province, Thailand. The basic properties of the lateritic soil are summarized in Table 1. RAP was obtained from rehabilitating the old asphalt pavement of Bureau Road No.2 in Nakhon Ratchasima province, Thailand. The original grain size distribution curves of RAP and lateritic soil are presented in Figure 1. The RAP replacement ratio was fixed at 30% by dry weight which is below the limitation of proper RAP replacement ratio ($< 50\%$) suggested by the previous study (Suebsuk *et al.*, 2014; Taha *et al.*, 2002).

The compaction test was performed to determine the maximum dry density (MDD) and the

Table 1. The basic properties of materials

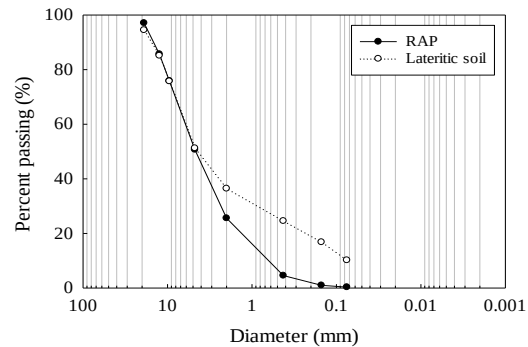
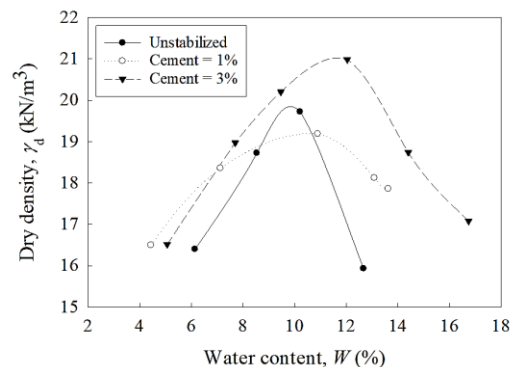
Properties	Clay	Lateritic soil	RAP
Liquid limit, LL (%)	37	31	
Plastic limit, PL (%)	28	14	
Plasticity Index, PI (%)	9	17	
Specific Gravity, G_s	2.67	2.58	2.35
Coefficient of uniformity, C_u	-	1.8	1.48
Coefficient of Curvature, C_c	-	80	8.57
Classification (USCS)	CL	GW	GW

optimum moisture content (OMC) of the RAP-soil blends. The standard Proctor was carried out following the testing procedure of ATSM D698.

The unconfined compression strength (UCS) test was conducted to determine the strength of RAP-soil blends. The UCS sample was prepared by oven-drying lateritic soil, and RAP was at 60°C before screening through sieve No. 4 (sieve opening 4.75 mm) to remove the larger size particle. The lateritic soil was replaced by RAP at 30% by dry weight before cement was admixed. The mixture was mixed thoroughly before the desired amount of water was added and mixed. The mixture was then compacted in a steel mold with dimensions of 50 mm diameter and 100 mm height. The sample's desired dry density and moisture content were at maximum dry density and optimum water content (Figure 2). The compacted samples were extruded and wrapped with a plastic bag. The samples were cured for 28 days in a controlled temperature and humidity room. After that the samples were unpacked and submerged under water for 2 hours before the UCS test.

The physical model was set up to install a stabilized RAP-lateritic soil column in the middle. The clay was desiccant by oven at 60°C for 48 hours. The dried clay was broken into small particles by light tamping with a rubber hammer. Standard sieve No. 4 was used to screen the larger particles. The distilled water was mixed with clay powder using a stirring blade until the water and clay became the paste at 1.5 times the liquid limit. The clay paste was then filled in a plastic tank and covered with plastic wrap, letting the clay absorb the water for about 3-4 days. After that, the slurry clay was filled in the PVC mold with a diameter of 150 mm and 300 mm high, connected to a circular steel plate. The vertical drainage path was assumed as half of model tank, which required a long period of consolidation.

To accelerate consolidation time, the small holes surrounding the surface of the PVC mold were provided to allow the horizontal drainage of water. The filter paper was attached to the drainage holes at the inner mold to confine the clay particles. After the clay was filled in PVC mold, the circular steel plate was laid on the clay surface. The plate also had

**Figure 1. Grained size distribution of RAP and lateritic soil****Figure 2. Compaction curves of RAP-soil blends at various cement contents**

drained holes, allowing the water to drain out vertically. The clay layer was consolidated by applying steel plates starting from a vertical stress at 2.9 kPa. The settlement of the clay layer was measured, and the next dead load was applied when the settlement reached 85% primary consolidation approximated using Asoaka's method. The stress increment was twice the previous stress. The final stress was 98 kPa and the clay model's thickness after the end of consolidation was 200 mm (Figure 3(a)).

The dead load on top of clay model was then removed. The steel casing with a 50 mm diameter was inserted vertically at the center of the clay layer (Figure 3 (b)-(c)). As a result, a 50 mm well at the middle of the clay model was created. The end-

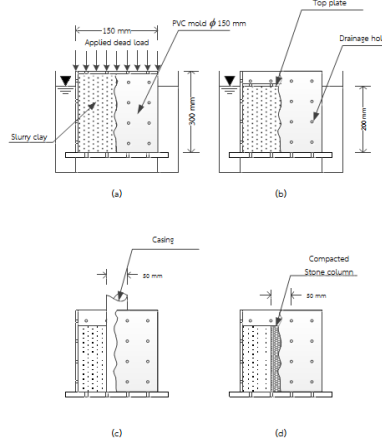


Figure 3. Installation of compacted stone column (a) Filling slurry clay in PVC mold and applying dead load (b) Desiring height of clay layer (c) Perpetrating a casing into clay layer (d) Inserting compacted stone column

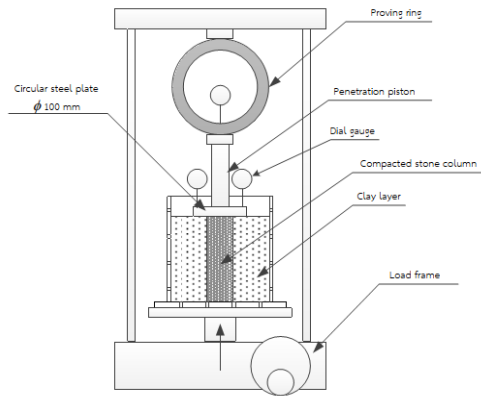


Figure 4. Schematic of load-settlement testing

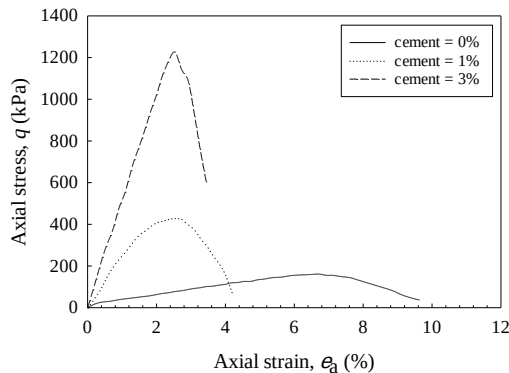


Figure 5. Unconfined compressive stress versus axial strain relationship of RAP-soil blends at various cement contents

bearing stabilized RAP-lateritic soil column with a 50 mm diameter and 200 mm height was installed the hole (Figure 3 (d)) by compacting the stabilized blend under standard Procter energy to achieve the 98% MDD. The physical model with the column was next cured in a water tank for 28 days, while the model without the column was subjected to the load-bearing test immediately.

After 28 days of curing, the physical model was taken from the water tank and kept in the air for about 30 minutes to allow the clay surface to dry. The load-bearing test was carried out by placing the circular steel plate with a dimension of 100 mm diameter and 10 mm thick on the top of the physical composite ground model. The thickness of the circular plate is sufficient to withstand the applied load, so that the deflection of the plate is neglected. A proving ring and two dial gauges were attached to the top plate to measure the vertical load and settlement, respectively.

The schematic of the load bearing test is presented in Figure 4. The load was applied by lifting the lower plate of the model vertically against the proving ring with a rapid uniform rate of 1 mm/min while the load and displacement were recorded. The testing was terminated at 25 mm vertical displacement.

Result and discussion

The result of the unconfined compressive strength (UCS) test of RAP-soil blends is presented in Figure 5. The unstabilized specimens exhibited strain-hardening behavior. On the other hand, the brittle response was clearly shown with an increased cement content. The axial stress increased while the axial strain at the peak strength decreased with the increased cement contents consistent with a previous study (Schnaid *et al.*, 2001). The higher cement content results in the stronger cementation bonds and hence the higher UCS (Figure 6). Rapid reduction of stress after the peak may be expected to be due to broken up of cementation bonds.

The load-settlement curves of composite clay grounds are presented in Figure 7. For the clay without a column, the bearing stress increased with displacement linearly up to a certain stress level. Afterward, the stress value was almost constant with further increased in displacement. The load-settlement response of the clay reinforced by an unstabilized RAP-lateritic soil column was similar to that of the clay ground but the bearing stress level was higher for the same displacement. This implied that the higher friction angle of RAP-soil blends contributes to the enhanced load capacity of the composite ground.

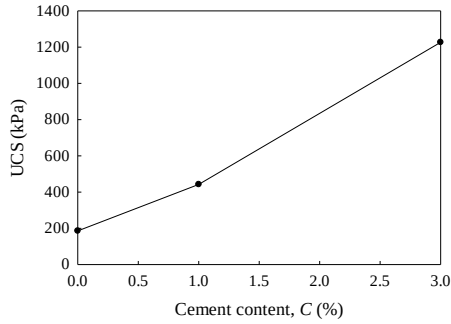


Figure 6. The variation of unconfined compressive strength of RAP-soil blends with cement content

The load-settlement curves of clay ground reinforced with the stabilized column are dependent upon the level of cement content. The bearing stress was higher for the column with higher cement content for the same vertical displacement. In other words, settlement decreased with the increased cement content. The load-settlement curve of the 3% cement column showed noticeable peak bearing stress then reduced to a lower value similar to that obtained from the unconfined compressive strength test. However, at the ultimate stress, the bearing stress is higher than that from the unreinforced clay ground and composite ground with unstabilized RAP-soil column. It was suggested that the stabilized column was further enhanced the bearing stress after failure.

The ultimate bearing capacity of composite ground reinforced by compacted stone column (q_{ult}) suggested by Han (2015) is expressed as follows:

$$q_{ult} = q_{ult,c}as + q_{ult,s}(1 - as) \quad (1)$$

where $q_{ult,c}$ = individual bearing capacity of the column, $q_{ult,s}$ = bearing capacity of the clay surrounding the column, and as = the area replacement ratio defined as the cross-sectional area of the column (A_c) to the tributary area (A_e).

The as depending upon the pattern of installation layout of the stone column, i.e. rectangular and pattern and triangular. In this study, the physical ground model and the stabilized column were in circular shape. The as is therefore calculated using the following equation:

$$as = \left(\frac{d_c}{D}\right)^2 \quad (2)$$

where d_c = diameter of the column, D = diameter of physical model. As such, the as was calculated to be 0.11. The $q_{ult,s}$ was obtained from the bearing

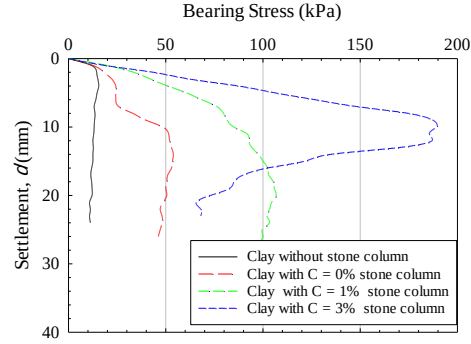


Figure 7. Load - settlement curve of clay layer reinforced by stone column

capacity of unreinforced clay (34.90 kPa). Based on the passive shear failure of the column, $q_{ult,c}$ can be approximately estimated as follows: (Han, 2015).

$$q_{ult,c} = 20S_u \quad (3)$$

where S_u = undrained shear strength of clay. In this research, $S_u = 4.84$ kPa. It is worth noting that Eq. 3 was derived for the cohesionless material with typical friction angle of 38° .

Eq. 3 suggests that $q_{ult,c}$ only depends on the undrained shear strength of clay and the friction angle of the column. This implies that even with the increase in cement content, the $q_{ult,c}$ remains unchanged. The same is not true for the composite ground with the cement stabilized column. Suksan and Horpibulsuk (2022) and Suksan *et al.* (2024) revealed that cement stabilization has a marginal effect on the increase in friction angle of cement stabilized RAP-lateritic soil blends but resulted in significant increase in cohesion. In other words, the $q_{ult,c}$ increases significantly with the increased cement content. With the increase in $q_{ult,c}$, the q_{ult} was expected to increase with cement content. The relationship of q_{ult} versus UCS of the RAP-soil column for various cement contents was then plotted and is presented in Figure 8. The q_{ult} increased proportionally with the increased UCS of the RAP-lateritic soil column.

Based on this finding, the q_{ult} of composite ground with the RAP-lateritic soil column was modified and is expressed as follows:

$$q_{ult} = \beta(UCS_c)as + q_{ult,s}(1 - as) \quad (4)$$

where the β is the constant taking into account the effect of confining stress from the surrounding clay on the bearing capacity of stabilized column. Based on the linear regression analysis, β was calculated empirically as 1.12.

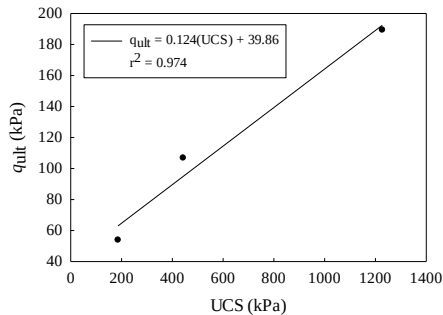


Figure 8. Bearing capacity of clay reinforced by stone column

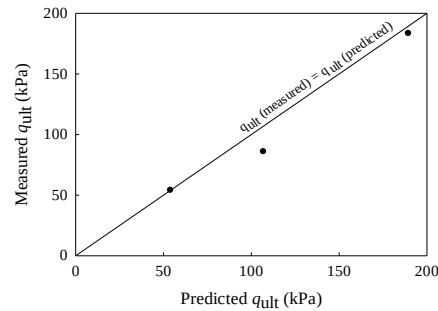


Figure 9. The comparison of the measured and predicted bearing capacity of the composite ground reinforced by RAP-Lateritic soil column

The predicted q_{ult} of the composite ground reinforced by the RAP-lateritic soil column via Eq. 4 was compared with the measured value as shown in Figure 9. It was evident that the predicted q_{ult} was in excellent agreement with the measured q_{ult} . It is concluded that the UCS can be used to determine $q_{ult,c}$ and the bearing capacity of composite ground for various compressive strengths of the column.

Conclusion

This study investigated the load-settlement behavior of soft clay reinforced by RAP-soil columns under static loading condition via the physical model. RAP was replaced with the lateritic soil at 30% and stabilized by Portland cement as a stabilized column. The evaluation of the effect of cement content on the bearing capacity of the composite ground was discussed. The conclusion of this study can be drawn as follows:

1. The unconfined compressive strength and stiffness of RAP-soil blends significantly increased with cement content. It was expected that the cementation bond was significantly contributed to the cohesion. The brittle response in stress-strain curves was more pronounced with when the cement content increased.
2. The load-settlement curve of the clay ground reinforced by the RAP-soil column was dependent upon cement content. At same bearing stress level, the resistance of vertical displacement increased with the increase of cement content.
3. The ultimate load capacity of composite ground significantly increased with cement content. The bearing capacity contributed from RAP-lateritic soil column was strongly governed by the UCS. Based in the proposed bearing capacity equation, the ultimate bearing capacity of the composite ground

with of RAP-lateritic soil column can be satisfactory predicted.

4. The studied load-settlement curve and the proposed bearing capacity equation are fundamental for numerical modeling and stability analysis of composite ground under loading condition. The present results can be refined with more field data. Field studies on the load-settlement response and the bearing capacity of the composite ground is therefore recommended for future research.

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