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Experimental study on the use of polyoxymethylene plastic waste as a granular column to improve the strength of soft clay soil

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The surging demand for sustainable and efficacious approaches of enhancing the ground has resulted in the investigation of novel waste materials. This study investigates the utilization of Polyoxymethylene (POM) as a granular column to ameliorate the ability of soft clay soil to resist horizontal loads. The study introduces a new implementation of polyoxymethylene columns as ground improvement approach to tackle the complexities related to soft clay soils. The capability of polyoxymethylene columns was analyzed through a sequence of laboratory experiments, containing engineering characteristic tests, unconfined compressive strength (UCS) tests, and consolidated isotropic undrained (CIU) triaxial tests. The effects of the number of columns, column diameter, column depth, substitute area ratio, depth penetration ratio, column aspect ratio, volume infusion ratio, and confining pressures, were evaluated to analyze the behavior of individual and clustered encapsulated polyoxymethylene columns. The findings verified a notable development in the ability of soft clay soil, when strengthened with polyoxymethylene columns, to oppose the lateral loads and maintain overall stability. Additionally, a regression analysis was implemented to establish a prediction model that estimates the increase in shear strength of POM columns based on different column dimensions. This model is a practical tool for evaluating the performance of reinforced soft clay soils in large-scale projects. This study not only accentuates the mechanical benefits of polyoxymethylene but also accentuates its environmental benefits, prescribing for the implementation of recyclable materials in ground renovation.

Keywords Ground improvement, Granular column, Strength, Soft clay, Polyoxymethylene

Soft clay soil is characterized by four factors; compressibility, shear strength, moisture content and permeability as discussed in studies, by Mohammed et al.[1] and Li et al.[2]. These soils can undergo deformations without breaking due to their plasticity and fine grained texture. When loaded soft clay soil tends to lose volume due to its compressibility leading to settling of structures built on it as highlighted by Pandey et al.[3]. The weak shear strength of clay makes it vulnerable to fracturing under stress posing risks to foundations and embankments. The properties of clay soils are greatly impacted by their high moisture content according to Zhao et al.[4]. These soils exhibit compressibility and lower load bearing capacity as noted by Ali et al.[5]. Moreover the build up of water pressure in clays during loading due to poor drainage weakens the material potentially hindering construction activities. The inadequate strength and high compressibility of soft clay soil can trigger settling and excessive settlement causing structures, like roads, buildings and other constructions requiring weight distribution and stability may crack or misalign as pointed out by Zaini et al.,[6]. Additionally the poor permeability of soft clay soil resulting in waterlogging increases the risk of soil collapse and complicates drainage efforts according to Zaini et al.[7,8]. The materials great flexibility and extensive deformations pose challenges, for compaction and stability. Safe and long-lasting building requires thorough evaluation of soft clay soil and, in many situations, specific ground improvement processes[9].

Yi et al.[10] and Rezaei-Hosseinabadi et al.[11] state that ground improvement solutions are necessary to improve soil engineering, especially in unstable or problematic soils like soft clay. Stabilising soil with lime or cement, speeding consolidation with preloading and surcharging, increasing soil density or replacing it with

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vibro-compaction or vibro-replacement, and reinforcing with geosynthetics are mentioned. The building and construction industry is prioritising sustainability by using recycled materials and eco-friendly methods[12,13]. Ground augmentation employs recycled plastics to build granular columns that stabilise unstable soils, according to Orekanti and Dommaraju[14] and Hilal and Hadzima-Nyarko[15]. The process involves underground vertical columns of compressed recyclable plastic waste like bottles or bags. Plastic columns reinforce the soil's load capacity[16,17]. Using plastic waste in granular columns reduces trash pollution and landfill overflow, improving environmental sustainability. Plastic columns are lightweight, corrosion-proof, and suitable for a variety of soil types and construction projects[18,19]. This creative approach promotes plastic reuse and recycling, which meets soil stability requirements and supports the circular economy.

Plastic trash is a big environmental issue, hence a multifaceted solution is needed. Limiting single-use plastics, encouraging reuse, and improving recycling procedures with new sorting and processing equipment should be the goals of laws and public education campaigns[20]. When recycled mechanically, polymers are melted and reformed; when recycled chemically, they are broken down into monomers for new polymers. Additionally, deposit-return schemes, extended producer responsibility (EPR) laws, and plastic-based product bans may improve waste management. Biodegradable polymers, sustainable packaging, public awareness, and trash management are needed to reduce plastic waste's environmental impact[21–23].

Plastic waste is a big issue for Earth's ecosystems. The most common types of plastic waste are PET beverage bottles, HDPE pipes and containers, PVC plumbing fixtures and medical equipment, LDPE plastic bags and wraps, PP packaging and automotive parts, and PS non-reusable cutlery and insulation[20]. Due to a global plastics manufacturing boom, 380 million kilograms of plastic will be produced yearly by 2020. This huge industry generates over 300 million kilograms of plastic waste annually. Kaur and Pavia[20] and Zhang et al.[21] reported global plastic manufacturing rates. Production rates for polymers were: 18.5 million kilograms of POM, 10.8 million kilograms of ABS, 5,100 kilotons of PC, and 30.3 million kilograms of PET. Zaini and Hasan[25,26] note that almost 8 million metric tonnes of plastic waste enters the oceans each year, endangering oceanic life and ecosystems. Practical solutions are needed to address the growing problem.

Poor plastic waste management causes land and water pollution, animal injuries, and the release of hazardous substances during decomposition or burning[21]. Microplastics from disintegrating plastics damage groundwater and surface water and enter human meals, harming health[20]. Landfill overflow and marine debris, caused by inadequately managed plastic rubbish, also harm ecosystems and biodiversity[27]. Using geotechnical engineering to improve the earth with plastic rubbish is a novel solution. Plastic trash stabilizes weak soils, improving compressibility and shear strength[28,29]. When blended with soil, lightweight plastic aggregate improves load distribution and reduces settling. This plastic waste management method improves soil performance and reduces dependence on conventional building materials, among other economic and environmental benefits.

Thus, employing Polyoxymethylene (POM) instead of traditional reinforcement materials minimises the demand for synthetic or less sustainable materials and gives an alternative raw material source. Understanding problematic soils and POM as an eco-conscious replacement for soft clay soils is crucial as its application in ground repair is growing. Despite the amount of literature on industrial waste (e.g., by Rezaei-Hosseinabadi et al.,[30]) and similar findings on particular factors, statistical research into a universal relationship is scarce. No research has examined using POM granular columns to change problematic soil qualities. Thus, this paper focuses on geotextile-encased POM columns under lateral stresses in unconfined compression testing. This research also examines how encapsulated POM columns effect soft reconstituted clay's shear strength and compressibility. Our working hypothesis is that (1) encapsulated POM columns can change the mechanical and physical properties of soft clay soils; (2) they can enhance the strength of soils of different dimensions; and (3) we can predict shear strength by combining a number of independent variables. Thus, this study seeks to (1) determine the mechanical and physical properties of soft clay soil and POM, (2) examine the strength of soft clay soil and soft clay soil reinforced with different-sized encapsulated POM columns, and (3) develop a regression-based correlation coefficient to characterise the impact of different-sized POM columns on soft clay soils.

Experimental procedures

Materials

Figure 1 exemplifies the locations where the study's materials were sourced. Polyoxymethylene (POM) was obtained from KHQ Industrial Supplies in Selangor, Malaysia, at 3°00'59"N, 101°33'55"E. This company is the region's leading provider of high-quality industrial and engineering products. The encapsulated POM, known for its macroscopic porous arrangement with substantial pore sizes, was integrated into the soil using a surrogate technique. The selected geotextile for encapsulating the POM-reinforced soft clay was the Polyester Non-woven Geotextile Needle Punched Fabric (MTS 130).

Kaolinite, with the chemical formula $Al_2Si_2O_5(OH)_4$, is composed of aluminium silicate hydroxide. It is notably fragile, particularly when moistened. The mineral's platy structure is hydrophilic, facilitating easy hydration to create a slurry, which results in a uniform soft clay. In this study, kaolin powder, one of the soft clay soil, characterized by its distinct plate-like morphology, was sourced from Kaolin (Malaysia) Sdn. Bhd in Selangor, Malaysia (4°9'48.6"N, 101°16'25.32"E). The kaolin used in the experiments contains 48% sand, as specified in Table 1. No additional sand was mixed with the kaolin. This composition, with 48% sand and 52% clay and silt, was utilized to assess the soil's response to the introduction of polyoxymethylene (POM) columns. The soft clay soil underwent a specialized compaction process to ensure the production of repeatable and homogeneous soft clay samples. Detailed properties and preparation methods are outlined in Table 1.

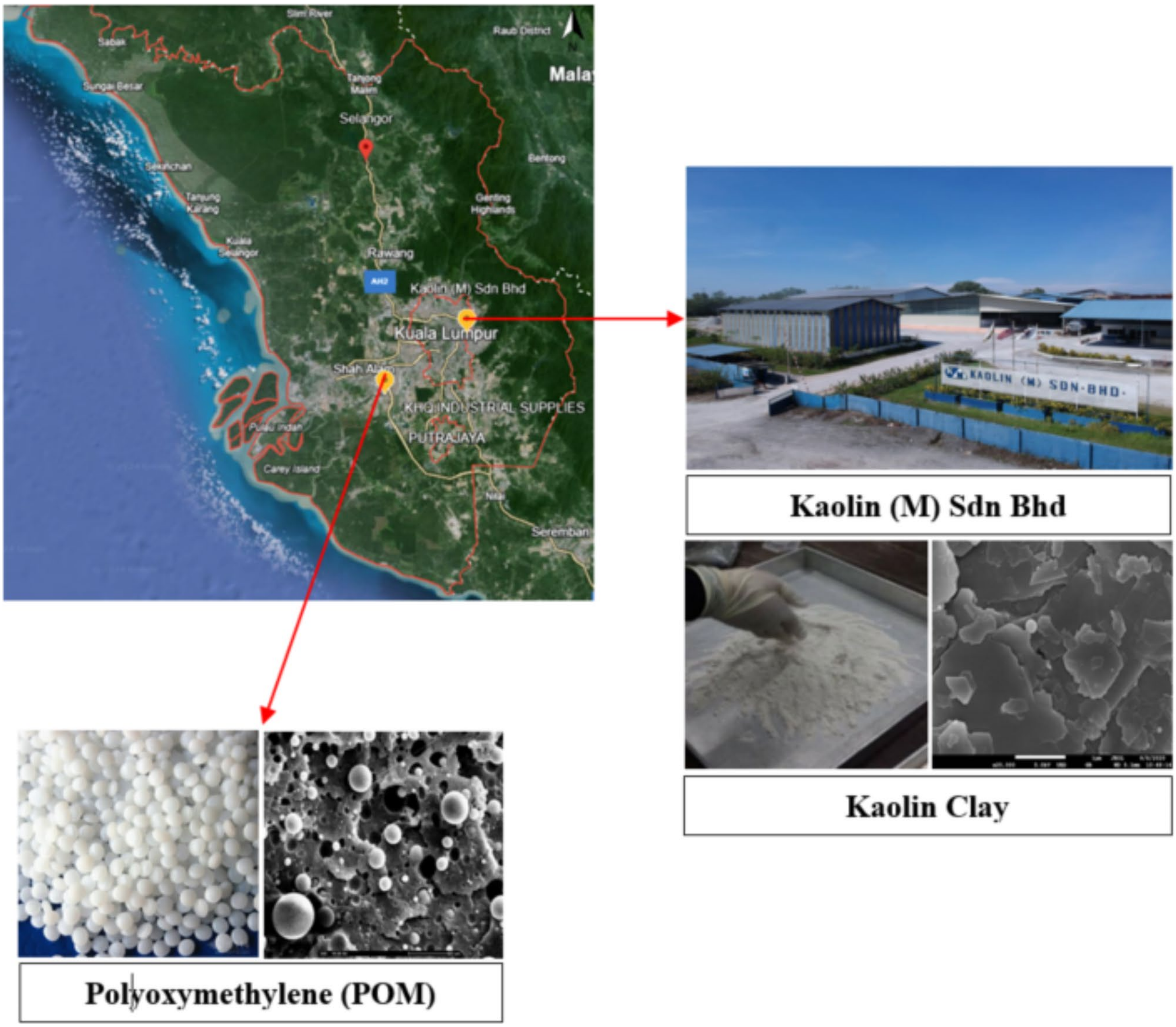


Fig. 1. Provenance of soft clay soil and POM.

Properties	Unit	Result
Gravel	%	0
Sand	%	48
Clay and silt	%	52
Specific gravity		2.62
Liquid limit	%	38
Plastic limit	%	32
Plasticity index	%	6

Table 1. Physico-mechanical properties of soft clay soil.

Experimental design

Sample preparation

The tests conducted in this study were performed following ASTM and British standards, as depicted in Fig. 2. For the CIU and UCT tests, the density of the POM columns was standardized using a consistent POM mass and the cavity fill volume. A uniform density of 0.921 g/cm^2 was utilized for the UCT and CIU sample preparation. From the compaction test, the soft clay sample was mixed with 20.91% water. The moistened soil was placed into a steel mould and compacted.

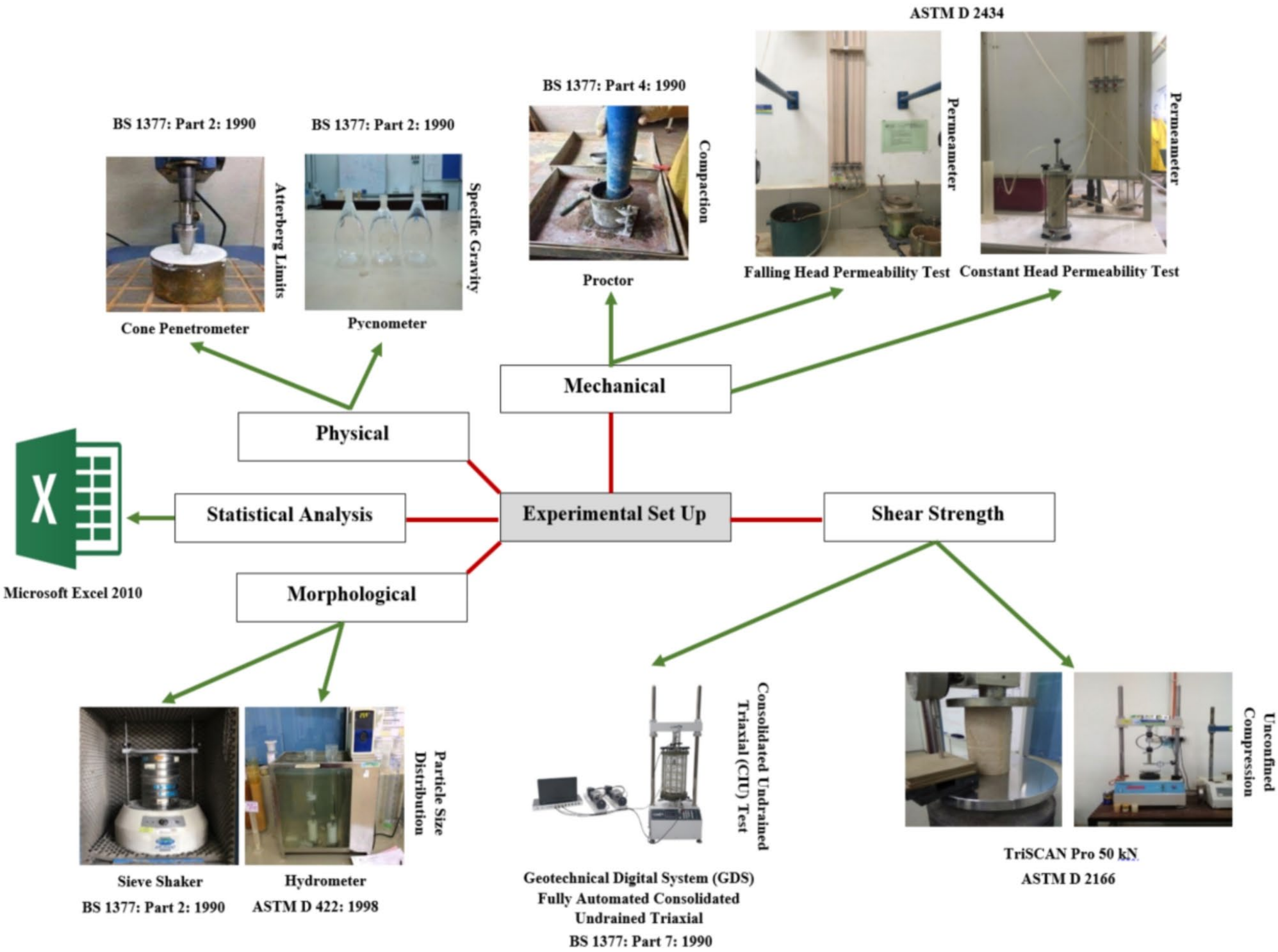


Fig. 2. Experimental setup and test standard utilized for the control and reinforced soft clay sample.

This study utilized stone columns with diameters ranging from 0.6 to 1 mm. The polyoxymethylene (POM) columns had diameters between 10 and 16 mm, and the POM particles for the laboratory tests were sieved to sizes ranging from 0.15 to 2.00 mm using BS sieves. The POM was introduced into a segregated mould lined with dual-layer rubber membranes and assembled in the CIU test program. Considering the granular nature of POM, these dual-layer rubber membranes were essential to prevent seepage. The POM column model supported the soil layer, replicating real-world construction scenarios to mitigate issues such as soil undulations, tilting, and uneven subsidence resulting emerging from the liquefaction of the substratum layers. A substitution technique was employed to create openings for the POM columns, where holes were drilled using bits of the desired diameter. This approach minimized soil disturbance and prevented surface heaving in the specimen.

Deployment of polyoxymethylene (POM) column

For soft clay-POM columns, the preparation process mirrored that of the unreinforced compaction test samples, as explained in the previous section. After compaction, holes were drilled for the POM columns using bits with 10–16 mm diameters, ensuring the samples remained confined within the mould to prevent expansion. The column depths were set at 30 mm, 50 mm, and 80 mm for partial penetration. Once formed, the specimens were gently removed from the mould, reserved in designated cases, and stabilized for at least 1 day to enable pore water pressure equilibration. The POM columns were encapsulated in geotextile to avoid excessive bulging and sewn into cylindrical moulds matching the borehole diameters. These geotextile-encased columns were then carefully inserted into the boreholes.

The POM material was compacted by allowing it to drop freely into the pre-drilled cavity 10 mm above the clay specimen's surface. A soft drill bit created the opening and gently compressed the POM, ensuring the column was void-free (see Fig. 3). To ensure consistent density within each POM column, the mass of POM was calculated based on the volume of the pre-drilled aperture, as outlined in Table 2. This approach guaranteed consistent density across all POM-reinforced soft clay specimens, ensuring reliable and reproducible experimental results.

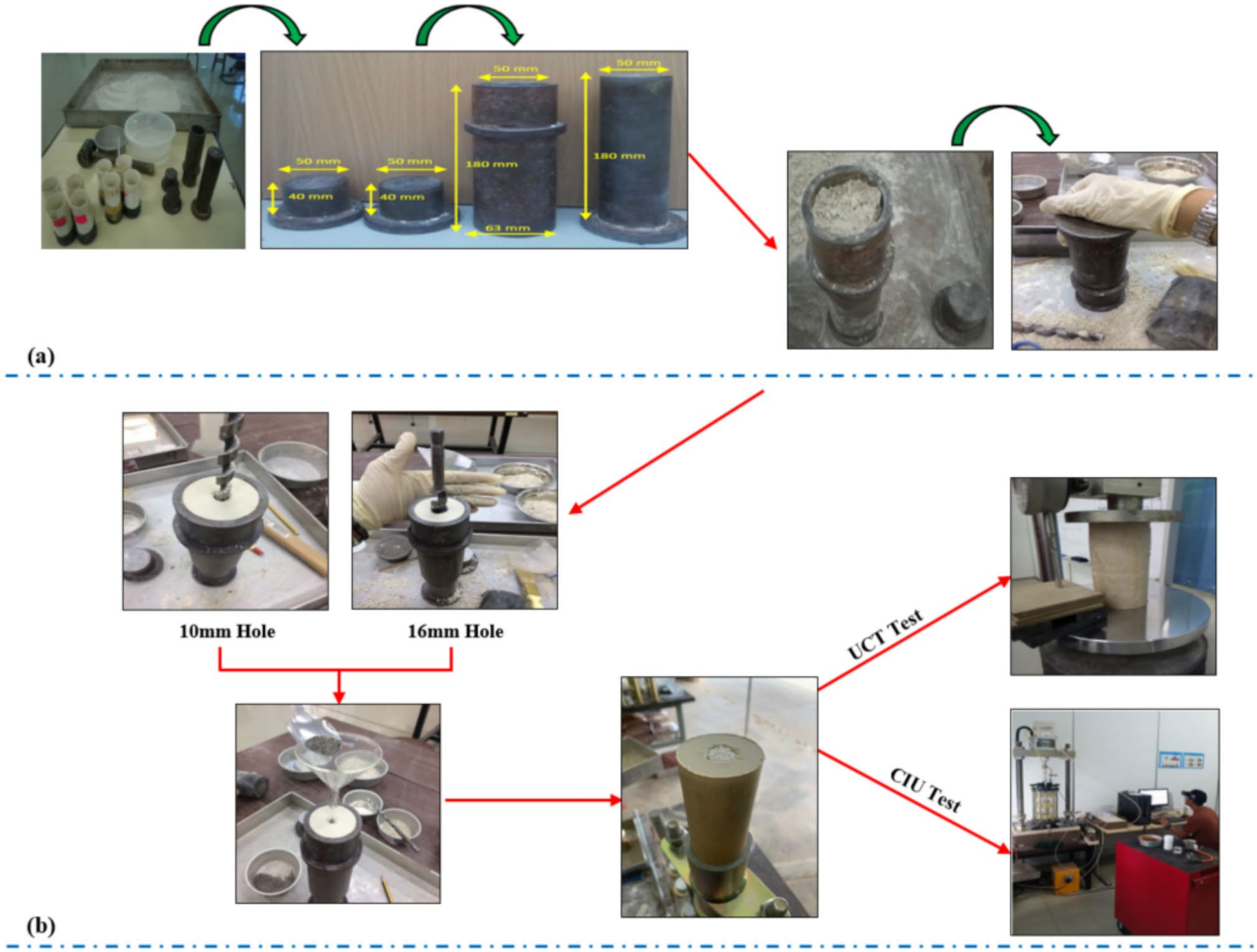


Fig. 3. Fabrication of: (**a**) soft clay sample; (**b**) soft clay sample with POM column reinforcement.

Diameter of column (mm)	Length of column (mm)	Volume of column with geotextiles (mm^3)	Density (g/cm^3)	Mass of POM (g)
10	30	2356.19	0.921	2.17
	50	3926.99		3.62
	80	6283.19		5.79
16	30	6031.86		5.56
	50	10053.10		9.26
	80	16084.95		14.81

Table 2. Density of POM columns at different sizes embedded in soft clay samples.

Configuration and dimensions of encased POM column pattern

In this investigation, two configurations of columns were employed: (1) Individual encapsulated POM column placement within individual specimens and (2) Specimens strengthened with clustered POM columns arranged in a triangular configuration to ensure equidistant placement. The column-to-column spacing was established by assessing the area ratio between the soft clay soil and the columns concerning the entire clay surface, guaranteeing efficient distribution of loads. The positioning of individual and clustered encapsulated POM columns was characterized by parameters such as the Substitute Area Ratio (SAR), Depth Penetration Ratio (DPR), Column Aspect Ratio (CAR), and Volume Infusion Ratio (VIR). Later analysis will use Fig. 4, which clearly shows individual and clustered encapsulated POM column architectures.

The prototype testing column size depends on broken material particle size (d) and column diameters (D). According to Hasan et al.[31] the D/d ratio should be near to prototype structures. We used POM particles from 0.15 to 2.00 mm and column widths of 10 and 16 mm for this experiment. Thus, D/d ratios ranged from 5 to 8. While these ratios are slightly lower than those typically encountered in prototype tests due to constraints related to column width aimed at avoiding border effects, they are deemed necessary for the study. The area ratio (Ar)

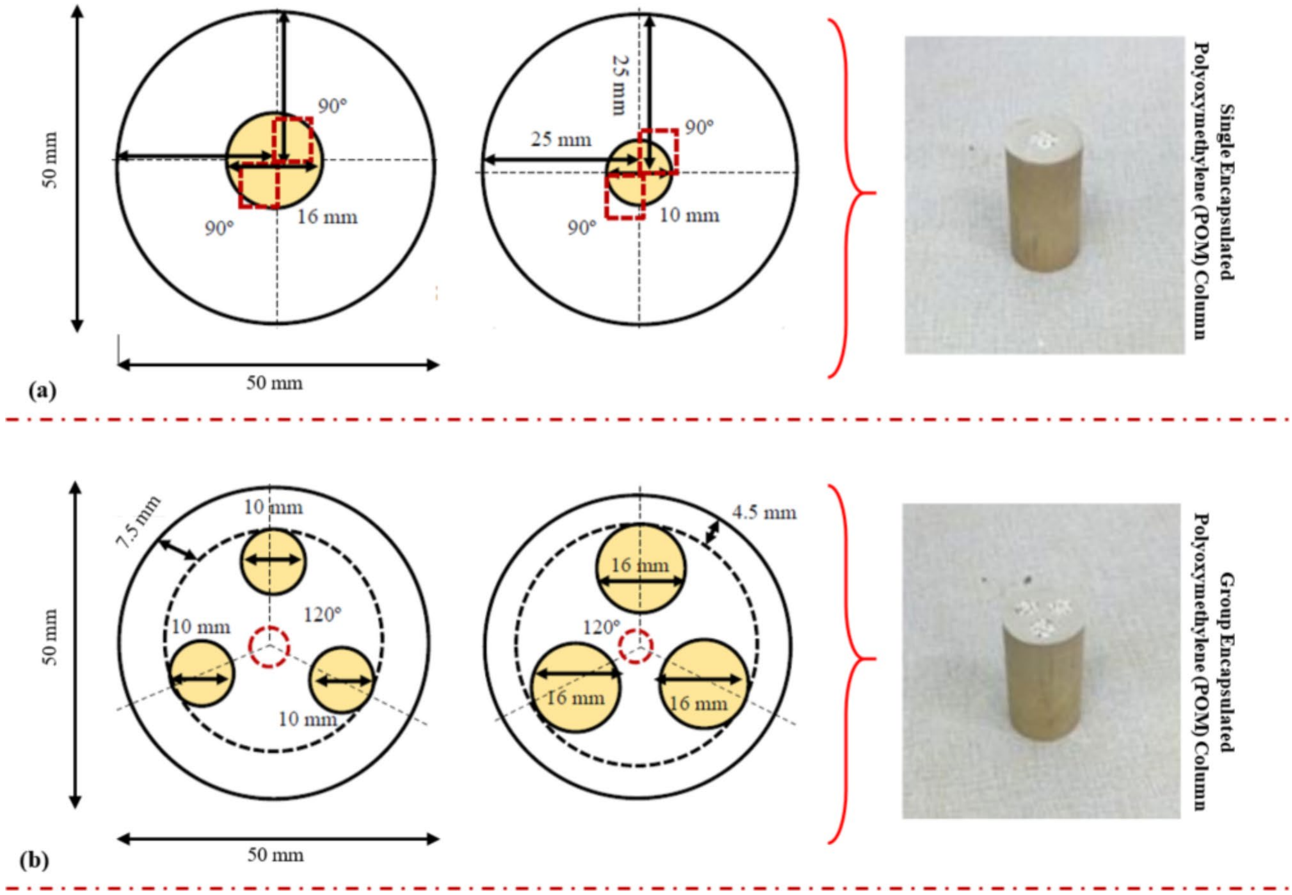


Fig. 4. Configuration of (**a**) individual and (**b**) clustered encapsulated POM column.

for individual columns ranged from 4 to 10.24%, while for clustered columns, it varied between 12.00% and 30.72%. The depth penetration ratio (DPR), column depth to specimen height, exhibited variations from 0.3 to 0.8 for semi-embedded columns.

Evaluation of the physical characteristics of the materials

This study investigates crucial physical characteristics of the soft clay soil strengthened with POM columns. Particle size distribution assessment for fine-grained soil particles flowing through a 63 µm sieve followed the guidelines stipulated in BS 1377: Part 2: 1990 for sieve analysis and ASTM D 422: 1998 for hydrometer analysis. The results, were graphically represented on a semi-logarithmic scale. These findings facilitated the classification of the POM material based on established soil classification systems.

Atterberg limits serve as a measure to quantify the plasticity of clay soil, assessing its moisture content, commonly referred to as plastic consistency. Given the fine particle size of soft clay soil, tests were conducted focusing on particles less than 63 µm. Depending on their dampness level, clay and soil typically manifest in various distinct conditions. The liquid limit, plastic limit test, and plasticity index, executed through the cone penetration method, adhere to the standards outlined in BS 1377: Part 2: 1990.

The determination of particle density for both POM and soft clay soil was conducted utilizing the small pycnometer test, following the guidelines outlined in BS 1377: Part 2: 1990. In this procedure, soft clay samples were carefully introduced into a small pycnometer, which had been previously filled halfway with distilled water. A vacuum chamber was employed for a day to eliminate air bubbles from the pycnometer and soft clay mixture. The pycnometer's soft clay soil and distilled water masses were reliably measured using this method. The relative density was measured using British Standard 1377: Part 4: 1990: 4. The gas jar method measured POM's particle sizes, which ranged from 2.36 to 0.6 mm.

Evaluation of the mechanical characteristics of the materials

The materials' compactness and permeability were tested to establish their mechanical properties. BS 1377: Part 4: 1990: 3.3 was followed to condense POM and soft clay soil to determine the connection between OMC and MDD. The technique requires a one-liter mould and 2.5-kilogram hammer. Three layers were compacted independently by releasing the hammer from a height of about 30 cm so it lowers freely and administering 25 strikes to each layer.

The permeability coefficient of soft clay soil was obtained by conducting the falling head test according to the ASTM D 2434 standard. The appropriate information was collected by utilizing an 8.2 cm diameter permeameter. The soil sample is prepared and placed in the permeameter. The sample must be compacted to the desired density and void ratio, which are consistent with the conditions expected in the field. The sample is first subjected to backpressure to ensure that it is fully saturated. This involves applying a gradual increase in water pressure to the sample while maintaining a constant low pressure at the outlet to force water into the voids of the soil, displacing air. The degree of saturation is monitored using a B-value, which is a measure of the pore pressure response under applied stress. A B-value close to 1.0 (typically above 0.95) indicates that the sample is fully saturated. This ensures that any air pockets in the sample have been expelled, and the pore spaces are completely filled with water. Once the sample is saturated, the falling head test is conducted. Water is allowed to flow through the soil from a standpipe, and the time it takes for the water head to fall from one level to another is recorded. The permeability coefficient is then calculated based on the change in water level over time, the dimensions of the soil sample, and the cross-sectional area of the standpipe.

Evaluation of unconfined compressive strength of the materials

The Unconfined Compression Test (UCT) was conducted following ASTM D 2166 to assess the soil's strength under axial loading without lateral confinement. Samples with varying substitute area ratios (4.00%, 10.24%, 12.00%, and 30.72%) were meticulously prepared for testing, each reinforced with non-woven geotextiles. These samples exhibited different depth penetration ratios (0, 30, 50, and 80 mm). 52 UCTs were carried out on reinforced soft clay soil, distributed across 13 batches containing four samples featuring diverse penetration depths. Six types of non-woven geotextiles were utilized to maintain uniformity, uniformly encasing each distinct trial with consistent cavity sizes. The density of POM specimens was maintained at 0.921 g/cm^2, while soft clays were 0.156 g/cm^2. Throughout UCT, stringent measures were implemented to ensure consistent density maintenance across all specimens, thereby upholding data reliability and integrity.

Evaluation of compressibility and shear strength characteristics of the materials

The study employed the Consolidated Isotropic Undrained (CIU) triaxial test to assess soft clay's compressibility and shear strength characteristics, both in its natural state and enhanced with encapsulated individual and clustered POM columns. The CIU test encompassed three distinct stages: saturation, consolidation, and shearing. Saturation was achieved until the B-Value surpassed 0.95, showing sufficient saturation, with backpressures of 100, 200, and 400 kPa utilized. Test specimens were homogeneously consolidated during consolidation under effective confining pressures equal to the backpressures, ensuring proper consolidation before shearing commenced. Undrained shearing of typically consolidated specimens proceeded at a uniform strain rate of 0.15 mm/min until axial strain reached approximately 20%. All CIU tests adhered to the standards specified in BS 1377: Part 7: 1990. For the CIU test, soil specimens were prepared by compacting them to optimal water content in cylindrical steel moulds measuring similar dimensions to UCT. Each mixture underwent the preparation of three samples. To maintain data consistency, the density of POM specimens was maintained at 0.921 g/cm^2, while that of the reference specimen stood at 0.156 g/cm^2, ensuring uniform density across all samples. Table 3 provides comprehensive details regarding the samples used in the study.

Statistical evaluation

Mathematical analyses were conducted utilizing Microsoft Excel 2016 to interpret the acquired data. One-way Analysis of Variance (ANOVA) was the statistical tool implemented to compare the physical and mechanical characteristics observed in the enhanced samples. The Fisher's Least Significant Difference (LSD) method was implemented to discern substantial disparities between means across various enhancements, maintaining a significance level of $p < 0.05$. Pearson's correlation analysis was also executed to elucidate the relationships between the physical parameters influencing the enhancement of strength. Error bars were strategically employed to denote notable discrepancies in results among the samples. Regression analysis was employed to establish a predictive equation for the strength enhancements of strengthened soft clay soil. This reinforcement was achieved using encapsulated Polyoxymethylene (POM) columns with varying dimensions, based on the formulation provided in Eq. (1). Finally, the selection of the best prediction model is validated and selected based on Mallow's C_p Criterion.

$$y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \ldots + \beta_{p-1} x_{i,p-1} + \epsilon \quad (1)$$

where y_i is the independent variable, x_i is the independent variable, β_0 is the intercept, $\beta_1, \beta_2, \ldots, \beta_{p-1}$ is the coefficient of regression for the explanatory variables and ε is the error term.

Results and discussion

Influence of encapsulated polyoxymethylene (POM) column on the physical characteristics of soil

Figure 5(a) and (b) illustrate the particle size distribution of the soft clay soil and polyoxymethylene (POM) samples. In Fig. 5(a), the particle size distribution of the soft clay sample exhibits characteristics reminiscent of well-graded sand, displaying grain sizes ranging from clay to fine sand. This distribution was derived by plotting the percentage passing against the corresponding particle diameter. Employing the AASHTO, it can be inferred that soft clay soil meets the criteria for clayey soil (Group A-7-6b).

For POM (as illustrated in Fig. 5(b)), particle size distribution analysis was conducted exclusively through dry sieve analysis due to the coarse nature of POM particles. A substantial portion of particles falls within the 0.063–0.1 mm range, corresponding to sizes ranging from fine sand to fine gravel. According to the USCS and

Coding	No. of column	Diameter of column (mm)	Area ratio, Ac/As (%)	Area ratio Ac/As with geotextile (%)	Depth of column (mm)	Depth penetrating ratio, Hc/Hs (%)	Volume of column, (mm^3)	Volume infusion ratio, Vc/Vs (%)
Control								
R	0	0	0	0	0	0	0	0
Individual encapsulated POM column								
S1030	1	10	4.00	2.19	30	0.30	2356.19	1.20
S1050	1	10	4.00	2.19	50	0.50	3926.99	2.00
S1080	1	10	4.00	2.19	80	0.80	6283.19	3.20
S1630	1	16	10.24	7.18	30	0.30	6031.86	3.10
S1650	1	16	10.24	7.18	50	0.50	10053.10	5.10
S1680	1	16	10.24	7.18	80	0.80	16084.95	6.49
Clustered encapsulated POM column								
G1030	3	10	12.00	6.57	30	0.30	7068.57	3.60
G1050	3	10	12.00	6.57	50	0.50	11780.97	6.00
G1080	3	10	12.00	6.57	80	0.80	18849.57	9.60
G1630	3	16	30.72	21.54	30	0.30	18095.58	9.30
G1650	3	16	30.72	21.54	50	0.50	30159.93	15.30
G1680	3	16	30.72	21.54	80	0.80	48254.85	19.47

Table 3. Model of programming and testing regimen for control and reinforced samples in CIU examinations. R, referenced sample; S1030, individual encapsulated with 10 mm and 30 mm of column diameter and column depth respectively; G1030, clustered encapsulated with with 10 mm and 30 mm of column diameter and column depth respectively, Ac, Area of column; As, Area of sample; Hc, Depth of column; Hs, Depth of sample; Vc, Volume of column; Vs, Volume of sample.

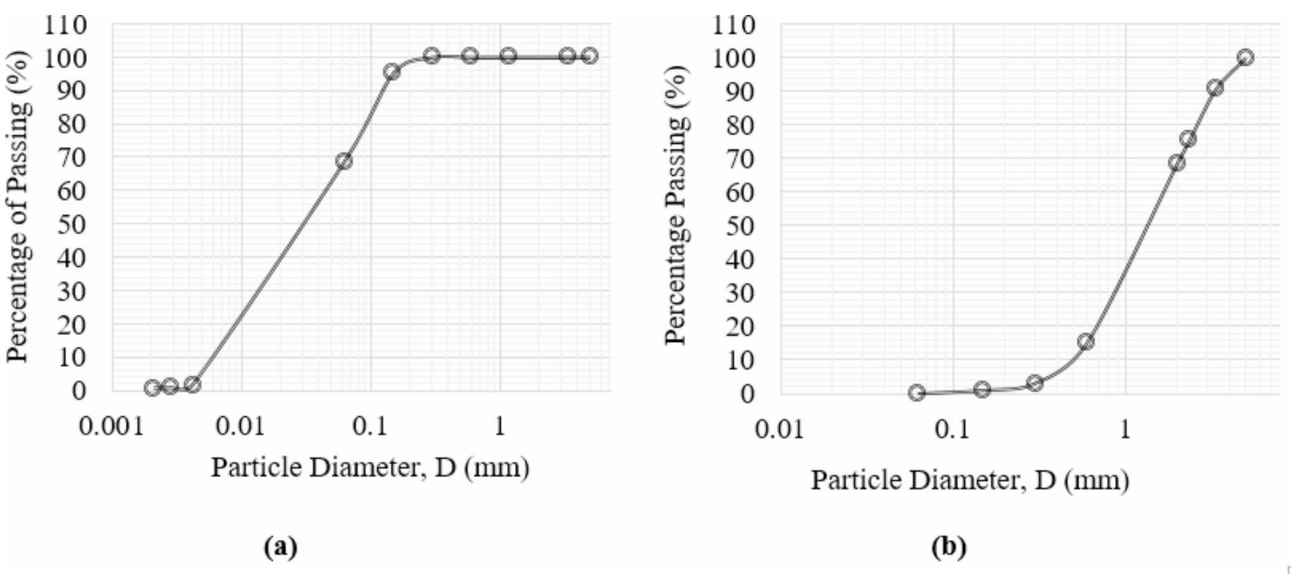


Fig. 5. Particle gradation of; (**a**) soft clay sample; (**b**) polyoxymethylene (POM) sample.

AASHTO, the POM sample is segmented as well-graded sand (SW) and falls within the A-1 group, specifically A-1-a.

The Atterberg limits test was exclusively performed on the soft clay soil, comprising smaller particles in compliance with standard requirements. Consequently, this test was not applied to POM samples. In this investigation, the liquid and plastic limits of the soft clay soil were determined to be 32% and 38%, with a resulting plasticity index of 6% based on a 20 mm penetration of the cone. Figure 6 depicts the penetration versus dampness level graph for the liquid limit and the classification of soft clay soil according to the plasticity chart. The plasticity chart reveals that the soft clay soil lies below the A-line, with a liquid limit of 41% and a plasticity index of 6%. Thus, it is categorized as ML (low plasticity silt).

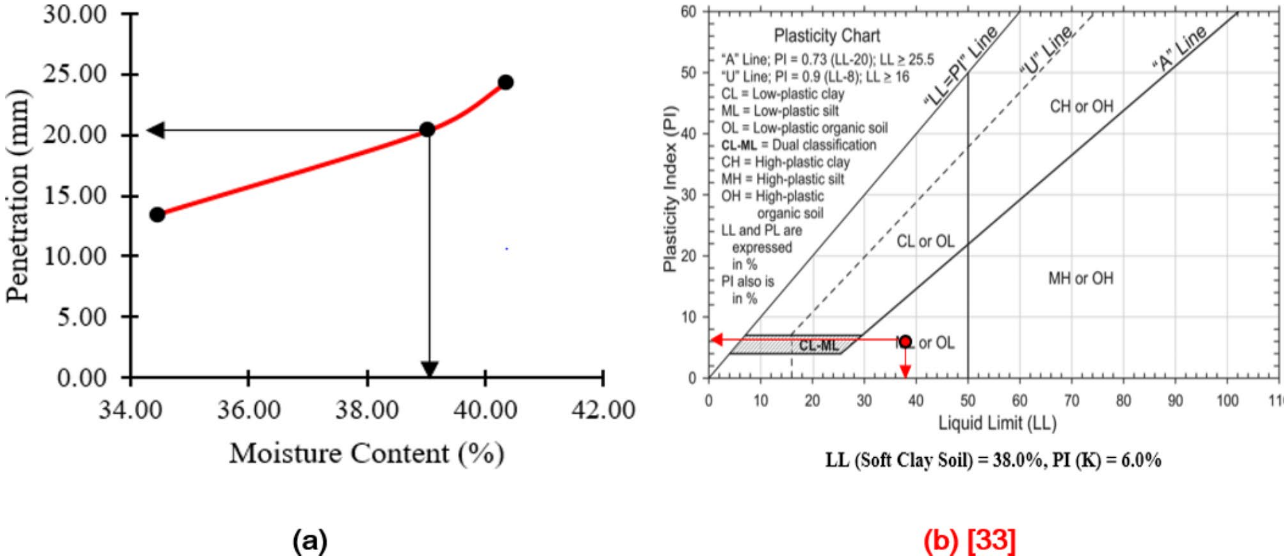


Fig. 6. Rheological characteristics of soft clay sample; (**a**) liquid limit of soft clay soil and; (**b**) soft clay soil classification based on plasticity chart.

The investigation determined the minimal and maximal densities of POM to be approximately 0.875 g/cm^2 and 0.921 g/cm^2, respectively. These density values were employed to install POM columns within the soft clay samples. It is pertinent to highlight that POM columns, besides serving as reinforcement, exhibit characteristics akin to vertical drains, which have the capacity to expedite the depletion of pore water pressure.

The particle density of soft clay soil is recognized to be 2.62, a figure that falls comfortably within the standard range for soil particle density. Zaini and Hasan[25] reported a modest increase in particle density of 2.64 for soft clay soil[32]. Zaini and Hasan[26] indicate that the specific gravity of the majority of soils often falls within the range of 2.60 to 2.80.

Mechanical characteristics of soft clay soil

Soft clay soil permeability was determined by the falling head test. Soft clay soil has a permeability coefficient of 2.35×10^{-1} m/s, as measured. Zaini et al.[33] found a substantially lower permeability coefficient (2.57×10^{-8} m/s) than ours. Zaini et al.[34] showed that fine-grained clay soils like soft clay soil had low permeability. This shows that the soils are impermeable and poorly drained. Compaction test findings showed that soft clay soil had an OMC of 20.91% and an MDD of 1.53 g/cm^3.

Influence of polyoxymethylene (POM) column deployment on the unconfined compressive strength

Soft clay samples with individual and clustered encapsulated polyoxymethylene (POM) columns had higher shear strength (Fig. 7(a) and (b)). As depicted in Fig. 7(b), the mean unconfined compressive strength across the five referenced samples was 12.82 kPa. Conversely, Fig. 7(a) illustrates that soft clay specimens fortified with an individual encapsulated POM column of 10 mm diameter and penetration heights at 30%, 50%, and 80% displayed average shear strengths of 17.51 kPa, 19.03 kPa, and 20.84 kPa, corresponding to enhancements of 36.58%, 48.44%, and 62.56%. Furthermore, when the soft clay samples were reinforced with an individual16 mm diameter POM column with penetration heights at 30%, 50%, and 80%, the average shear strengths measured 16.93 kPa, 21.69 kPa, and 25.95 kPa, respectively, showcasing improvements of 32.06%, 69.19%, and 102.42%. Notably, the highest enhancement in shear strength, recorded at 102.42% (highlighted by a gold box), was achieved with a 16 mm diameter column and an 80 mm height. Conversely, the lowest improvement, at 32.06% (highlighted by a blue box), was observed with a 16 mm diameter and a 30 mm height. Of particular significance, the 16 mm diameter column with an 80 mm height demonstrated the most substantial enhancement in shear strength among all examined samples, offering promising potential for augmenting the strength of soft clay soil.

This investigation used a triangular arrangement to strengthen the soft clay specimens with clustered-encapsulated POM columns. As depicted in Fig. 8, the strength of soft clay samples strengthened with 10 mm diameter clustered-encapsulated POM columns, with penetration heights of 30%, 50%, and 80%, registered at 17.48 kPa, 18.88 kPa, and 19.71 kPa, respectively, indicating shear strength enhancements of 36.35%, 47.27%, and 53.74%. For clustered comprising three 16 mm diameter columns with penetration depths of 30%, 50%, and 80%, the average shear strengths were 15.20 kPa, 20.02 kPa, and 21.96 kPa, respectively, corresponding to improvements of 18.56%, 56.16%, and 71.29%. Among the samples tested, the clustered-encapsulated POM columns with a 16 mm diameter and a penetration depth of 30 mm exhibited the lowest shear strength enhancement, recorded at 18.56%. Using 10 and 16-mm diameter columns, the strength exhibited a consistent increase corresponding to the depth penetration ratio, ultimately peaking at 80%. This phenomenon was observed across specimens reinforced with individual and clustered three POM columns, signifying an enhancement in undrained shear

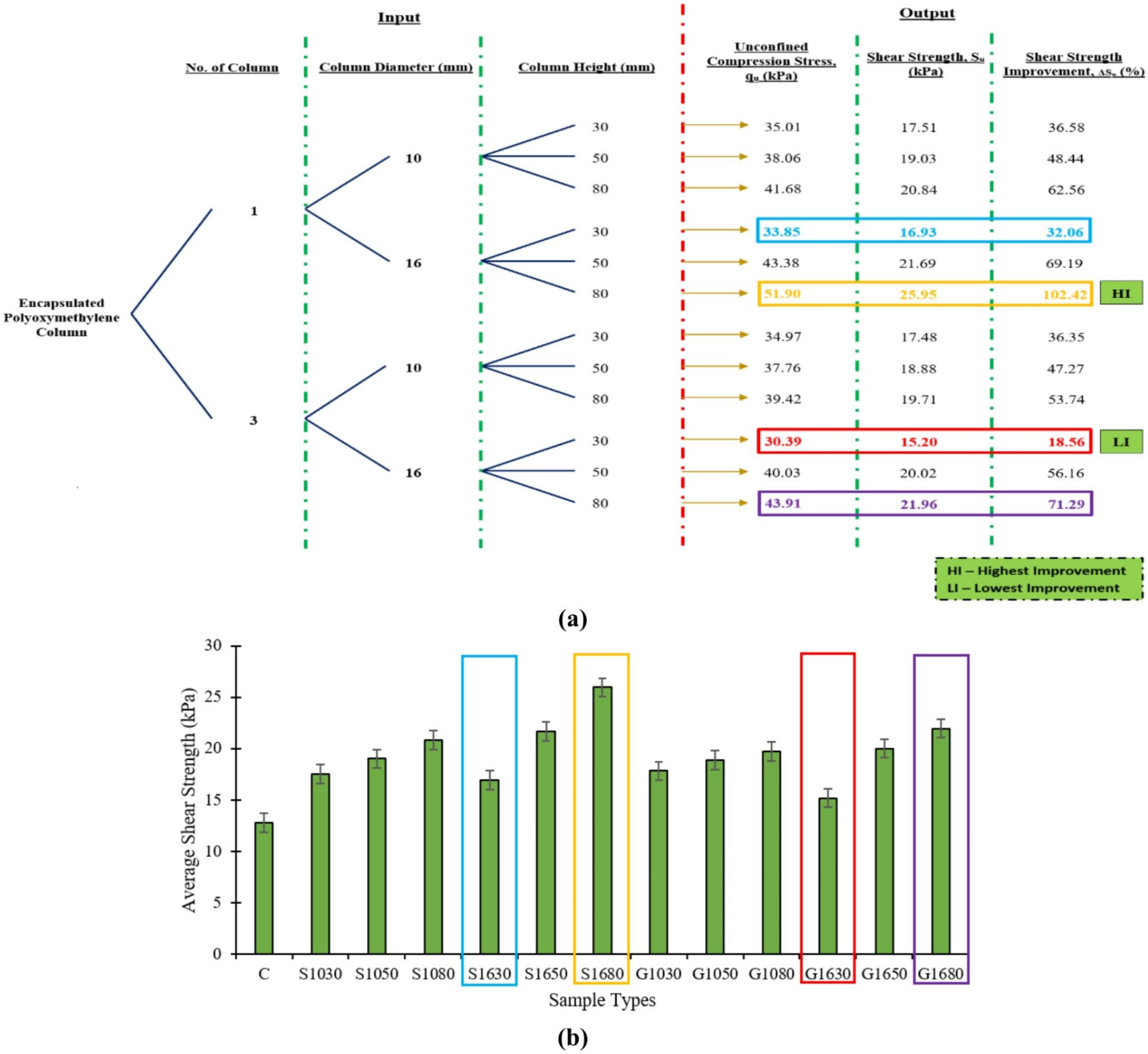


Fig. 7. Strength improvement of soft clay soil strengthen with encapsulated POM columns. Yellow box denotes the highest shear strength improvement in an individual encapsulated POM column; blue box indicates the lowest improvement in an individual encapsulated POM column; purple box highlights the highest improvement in a clustered encapsulated POM column; red box represents the lowest improvement in a clustered encapsulated POM column.

strength. The data elucidates that reinforcement, whether through individual or clustered-encapsulated POM columns, effectively elevates the strength characteristics of the specimens. The work presented by Miranda et al.[13] demonstrated a significant increase in the efficiency of increasing the aspect filler size as to improve the mechanical behaviour of the column-soil composite when a geotextile was installed. The geotextile encasement will help in great deal by consolidating the aggrigates from downward side and developed the same property as semi-rigid pile which will increased the strength. Strikingly, the results of this study support those of Hasan et al.[28], which further affirms the statement about the intensity of the geotextile encasement effect in improving the soft clay soil strength.

Influence of substitute area ratio (SAR) on the soft clay soil shear strength

As depicted in Fig. 8, a clear correlation emerges between SAR and soft clay specimens' corresponding strength changes. Comparative analysis with the reference specimen reveals noteworthy enhancements in shear strength upon reinforcement with individual and clustered encapsulated polyoxymethylene (POM) columns across various SAR values, ranging from 4.00 to 30.72%. This reinforcement yielded a substantial increase in shear strength from the baseline value of 12.82 kPa to a peak improvement of 25.95 kPa. Furthermore, it is noteworthy that the strength of specimens reinforced with an individual encapsulated POM column, featuring a SAR of

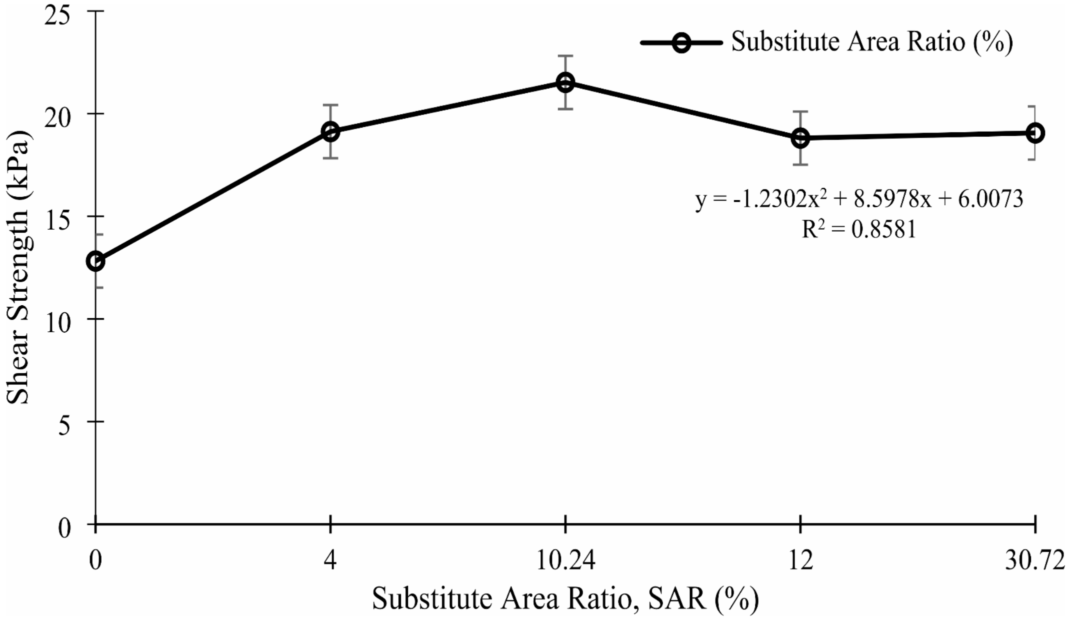


Fig. 8. Correlation between the substitute area ratios (SAR) with the strength of soft clay soil.

4.00% (as observed in samples S1030, S1050, and S1080), exhibited a slightly lower performance compared to those reinforced with a 16 mm diameter column (with a SAR of 10.4%, as seen in samples S1630, S1650, and S1680), recording an average shear strength of 21.52 kPa. The percentage disparity between these two configurations amounted to 12.53%.

Moreover, the mean shear strength of a clustered-encapsulated POM column with a substitute area ratio (SAR) of 12.00%, as observed in samples G1030, G1050, and G1080, was marginally lower compared to that of a clustered-encapsulated POM column utilizing a 16 mm diameter column (SAR = 10.4%), resulting in samples S1630, S1650, and S1680, with a mean shear strength of 19.06 kPa. The percentage difference between these two configurations amounted to 1.33%. Figure 8 vividly portrays that the maximum strength was achieved when the soft clay sample was strengthened with an individual encapsulated POM column at SAR = 10.24% (sample S1680). Consistent with this finding, the arrangement of individual encapsulated POM columns (mean shear strength = 20.33 kPa) emerged in a larger strength of soft clay contrasted with a clustered-encapsulated POM column (mean shear strength = 18.94 kPa), with a per cent discrepancy of 7.34%. Using granular columns demonstrated that the SAR substantially affected the soil's degree of improvement, as Li et al.[2] documented.

The observed variation in strength, particularly the lowest strength recorded with a clustered of 16 mm diameter POM columns at a height of 30 mm, can be attributed to inadequate column depth. Insufficient column depth restricts effective load transfer and distribution into the surrounding soil. The short columns offer minimal interaction surface, leading to inadequate frictional resistance and bonding. Additionally, they fail to provide substantial vertical confinement to resist lateral soil movement. Moreover, the overlapping zones of influence from multiple short columns do not penetrate deeply enough to reinforce the soil significantly.

Additionally, the superior shear strength attained by an individual encapsulated POM column with a diameter of 16 mm and a height of 80 mm might be attributable to its increased column depth. At critical depth ratio of 0.8, the load were distributed uniformly which expands the surface area for more effective bonding, encourages vertical confinement, and improved stability. This finding is consistent with the result obtained by Zaini and Hasan[25]. At R^2 value of 0.8581, showing that 85.81% of the strength data variation of soft clay soil is accounted for by the utilization of POM columns in terms of SAR.

Influence of depth penetration ratio (DPR) on the soft clay soil shear strength

As depicted in Fig. 9, the effect of DPR on the strength of soft clay soil strengthened with individual encapsulated polyoxymethylene (POM) columns and clustered encapsulated POM columns is elucidated. Compared to the reference specimen, individual and clustered encapsulated POM columns demonstrated significant improvements in strength at DPR values of 0.3, 0.5, and 0.8. Specifically, for individual encapsulated POM columns, the strength exhibited increments from 12.82 kPa to 17.51 kPa at DPR = 0.3, 19.03 kPa at DPR = 0.5, and 25.95 kPa at DPR = 0.8. Similarly, clustered encapsulated POM columns showcased enhancements from 12.82 kPa to 17.48 kPa at DPR = 0.3, 18.88 kPa at DPR = 0.5, and 21.96 kPa at DPR = 0.8. Remarkably, the maximum enhancement in strength was consistently observed at DPR = 0.8, suggesting a critical DPR of 0.8. Zhang et al.[21] and Mistry et al.[12] suggested that the pivotal column depth should fall within 5–8 times the width of the column, with DPR serving as a pivotal parameter for augmenting strength enhancement in clay soil. Short columns transmit substantial loads to the column's bottom, prompting penetration into the underlying clay. In contrast, longer columns lead to reduced penetration due to fewer loads transferring to the base of the column.

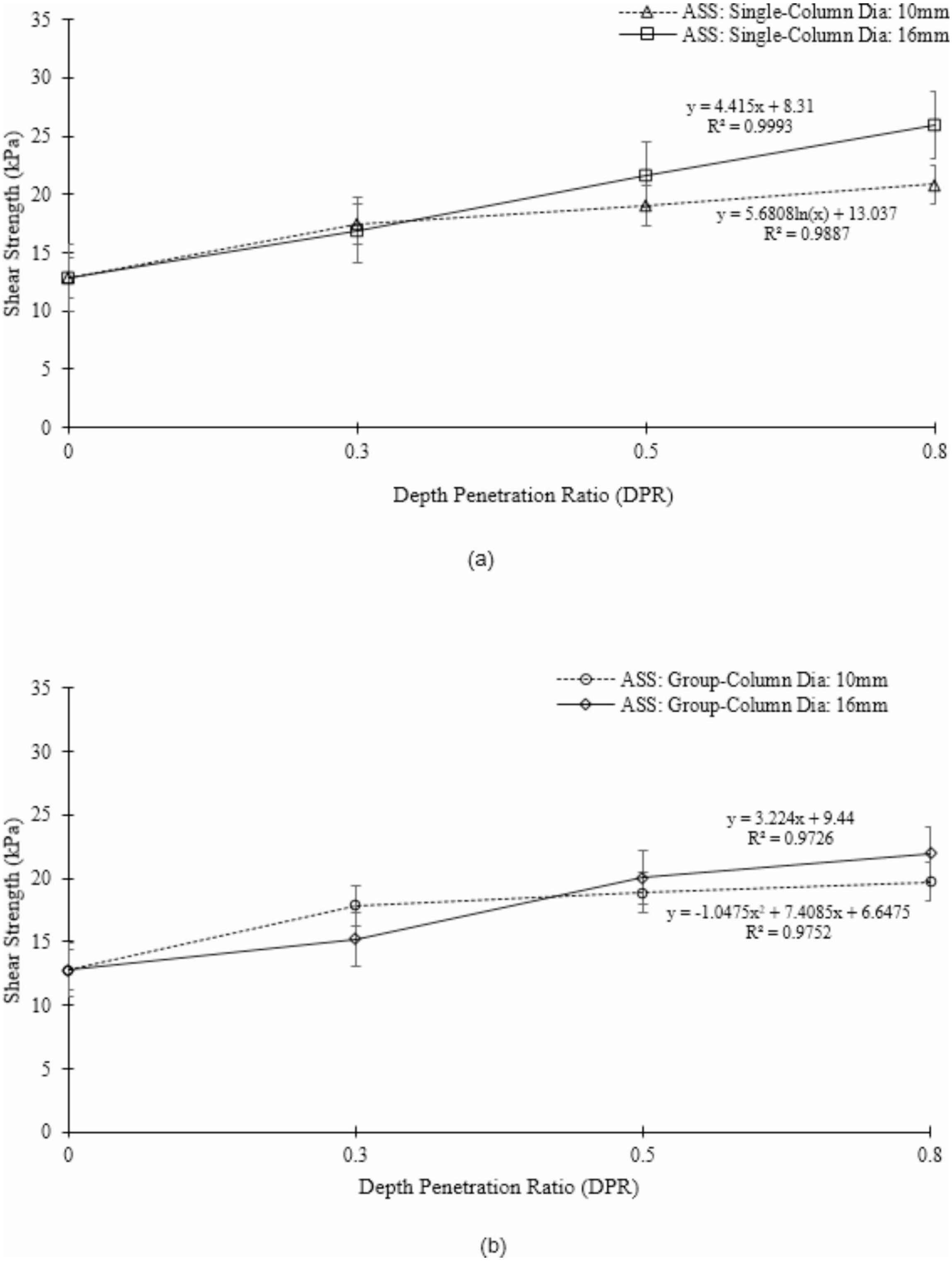


Fig. 9. Effect of depth penetration ratios, DPR on the shear strength of: (**a**) individual and; (**b**) clustered encapsulated POM column of soft clay soil.

The behaviour of polyoxymethylene (POM) columns can be analogized to that of piles in certain aspects. Similar to encased stone columns, the load-bearing capacity of POM columns is intricately linked to the strength of the surrounding soil. However, unlike encased stone columns, the load-bearing capacity of POM columns gradually diminishes as the stiffness of the geotextile increases. This results in a reduction in lateral bulging of the columns. This observation, as evidenced in studies conducted by Kaur and Pavia[35], is attributed to the attenuation of stress circulation within the soil with higher geotextile stiffness, thereby enhancing column stability. Encapsulating columns with geotextiles facilitates higher compaction levels, ultimately improving soil shear strength, as highlighted by Prasad and Satyanarayana[36].

As illustrated in Fig. 9, there is a discernible trend of increasing strength of soft clay soil with higher DPR values. However, while higher DPR values contribute to this increase, it is essential to note that the enhancement of shear strength is not solely contingent on the DPR of individual and clustered encapsulated polyoxymethylene (POM) columns. The substitution of soft clay with rigid materials like POM, coupled with the encapsulation of columns with geotextiles for drainage assistance, plays a pivotal role in driving the observed improvements. Therefore, the substantial raise in strength percentages can be connected to the increasing penetration of individual and clustered-encapsulated POM columns. Moreover, larger-diameter encased POM columns demonstrate superior performance compared to smaller diameters, primarily due to the harnessing of increased confining forces within the more enormous columns. This finding is consistent with Mohammed et al.[1] and Zaini et al.[33] investigation. As seen in Fig. 9(a) and (b), the regression analysis yielded R^2 values of 0.9887 and 0.9993 for reinforced soft clay soil with individual encapsulated POM columns having diameters of 10 and 16 mm, respectively. For the clustered encapsulated POM columns with the same diameters, the R^2 values obtained were 0.9726 and 0.9752, respectively. These results demonstrate that 98.87%, 99.93%, 97.26%, and 97.52% of the variation in the strength of soft clay soil is explained by the deployment of POM columns in terms of DPR.

Influence of column aspect ratio (CAR) on the soft clay soil shear strength

Figure 10 illustrates the effect of CAR on the strength of soft clay soil strengthened with individual and clustered encapsulated polyoxymethylene (POM) columns. It is evident from the figure that the peak strength for strengthened soft clay soil was achieved at a pivotal column depth of 0.8 for all specimens strengthened with individual and clustered encapsulated POM columns, corresponding to CAR values of 8.0 (S1080 and G1080) and 5.0 (S1680 and G1680) with strengths of 20.84 kPa, 25.95 kPa (for individual encapsulated POM column), 19.71 kPa, and 21.96 kPa (for clustered encapsulated POM column).

The maximum enhancement in strength was identified in S1680, with a strength of 25.95 kPa at CAR = 8.0, while the lowest enhancement was noted in G1630, with a strength of 15.20 kPa at CAR = 1.88. Furthermore, most soft clay soil strengthened with individual encapsulated POM columns exhibited higher strength compared to those strengthened with clustered encapsulated POM columns, with three samples (G1630, G1030, and G1050) displaying the minor strength improvement, with a strength of 18.56 kPa, 17.48 kPa, and 18.88 kPa respectively.

Changes in column diameter and height led to variations in CAR values. Notably, while an increase in CAR did not always translate into a continuous rise in shear strength, the CAR value significantly influenced the enhancement in strength of reinforced soft clay soil owing to its correlation with various column dimensions. Figure 11 demonstrates that the peak strength was attained at CAR = 8.0, corresponding to a pivotal column depth of 10 mm diameter of individual encapsulated POM column. Further increases in CAR values resulted in reduced strength of strengthened soft clay soil.

This investigation's outcomes align with prior research by Zhao et al.[4], all of which similarly observed that the most substantial enhancements in strength peaked at critical column depths. The implementation of POM columns for soil enhancement, particularly concerning CAR ratios, has demonstrated a significant impact on the extent of strength augmentation in soft clay soil, consistent with the observations made by Hasan et al.[28] and Ali et al.[5]. The escalation in strength can be ascribed to the heightened interlocking between the native soil and the POM column particles, facilitated by the surface adhesion of the geotextile, thereby augmenting the shear characteristics of the interface. However, it is imperative to acknowledge that while there is an augmentation in strength, this improvement is not exclusively contingent on the CAR value of individual and clustered encapsulated POM columns. As observed in Fig. 10(a) and (b), the regression analysis yielded R^2 values of 0.9895 and 0.9969 for reinforced soft clay soil with individual and clustered encapsulated POM columns having diameters of 10 mm. For the 16 mm diameter encapsulated POM columns, the R^2 values obtained were 0.9434 and 0.9925, respectively. These results demonstrate that 98.95%, 99.69%, 94.34%, and 99.25% of the variation in the strength of soft clay soil is explained by the deployment of POM columns in terms of CAR. The high R^2 values indicate a strong relationship between the implementation of POM columns and the augmentation in strength, thus validating the effectiveness of this soil improvement technique.

Influence of volume infusion ratio (VIR) on the soft clay soil shear strength

The effect of the volume penetration ratio (VIR) on the strength of soft clay soils was scrutinized, as illustrated in Fig. 11. The incorporation of both individual and clustered encapsulated polyoxymethylene (POM) columns as reinforcements for soft clay soil resulted in a notable enhancement of strength, elevating it from 12.82 kPa to a significant improvement of 25.95 kPa across all VIR values compared to the reference specimen. Intriguingly, the highest peak VIR value (VIR = 19.47) depicted in Fig. 12 did not correspond to the utmost augmentation in strength, as the strength recorded at VIR = 19.47 stood at 21.96 kPa. In contrast, the most diminutive peak VIR (VIR = 1.2) did not yield the lowest enhancement in strength, with the recorded strength being 17.51 kPa. Notably, the peak shear strength, indicative of the maximum enhancement in strength, was observed when POM was employed as an individual encapsulated fragmented column at a pivotal column depth of 0.8 with a column diameter of 16 mm. Consequently, it can be inferred that the VIR value is intricately linked to the column dimensions, with an escalation in column dimensions resulting in an augmentation of the VIR value. However, while an escalation in VIR value does not guarantee sustained progress in strength, it does impact the capability of the soil-strengthen encapsulated POM column. When the soil undergoes expansion, particle density shrinks, resulting to a reduction in strength and abrupt stress, weakening the stress-stress relationship as interparticle bonds break upon the cessation of expansion or contraction.

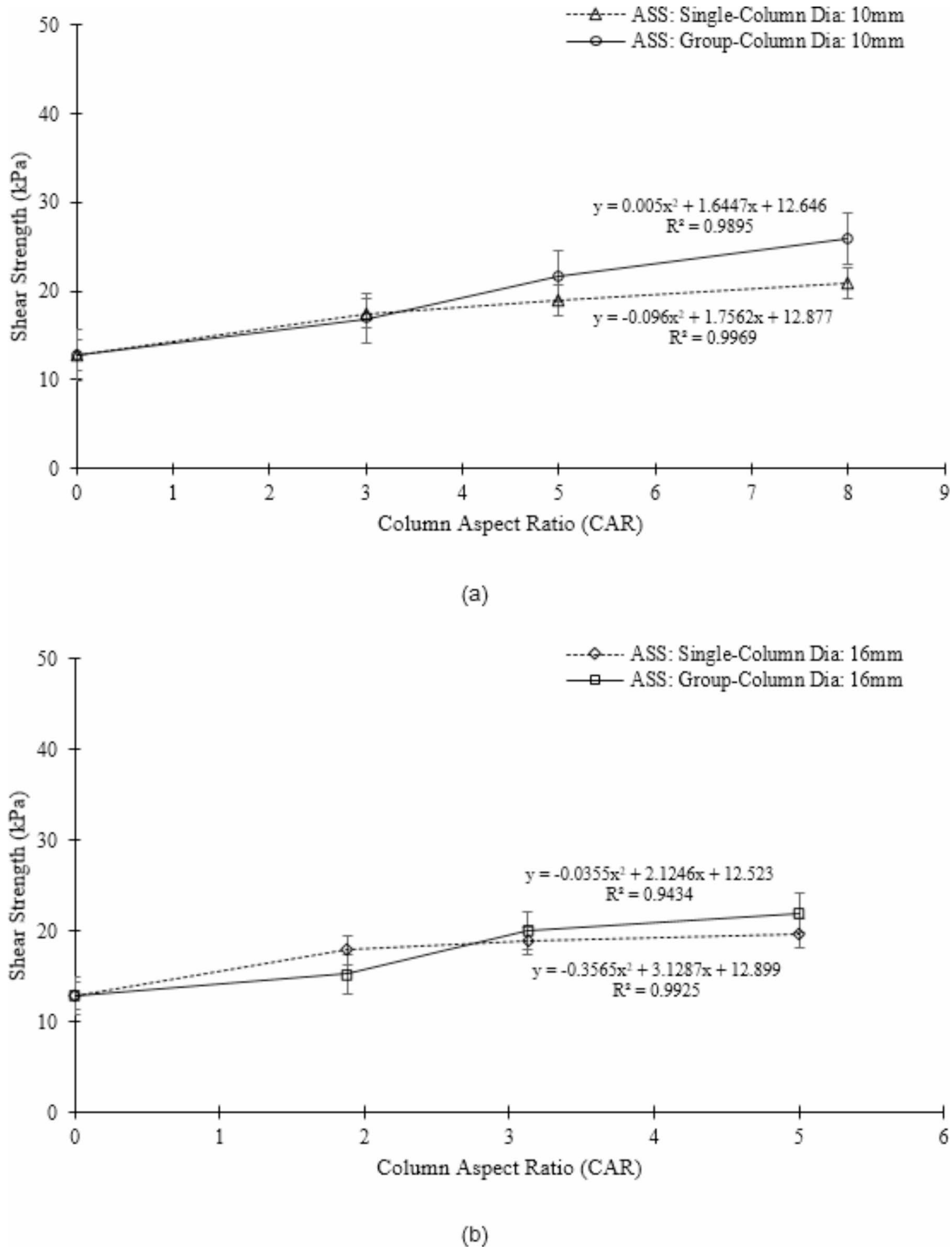


Fig. 10. Effect of column aspect ratios, CAR on the shear strength of: (**a**) individual and; (**b**) clustered encapsulated POM column of soft clay soil.

This assessment corroborates the results of Hasan et al.[28], emphasizing the significance of the SAR of the column in influencing the observed peak in strength improvement. The relatively small SAR of the column impacts the adjacent column region, thereby enhancing particle interlocking and bonding within the soft clay soil. Conversely, the diminished performance of the POM column can be attributed to the activation of more tremendous confining pressures within the more enormous columns, a trend consistent with the observations in this study. The escalation of confining stresses in smaller-width columns results in heightened column

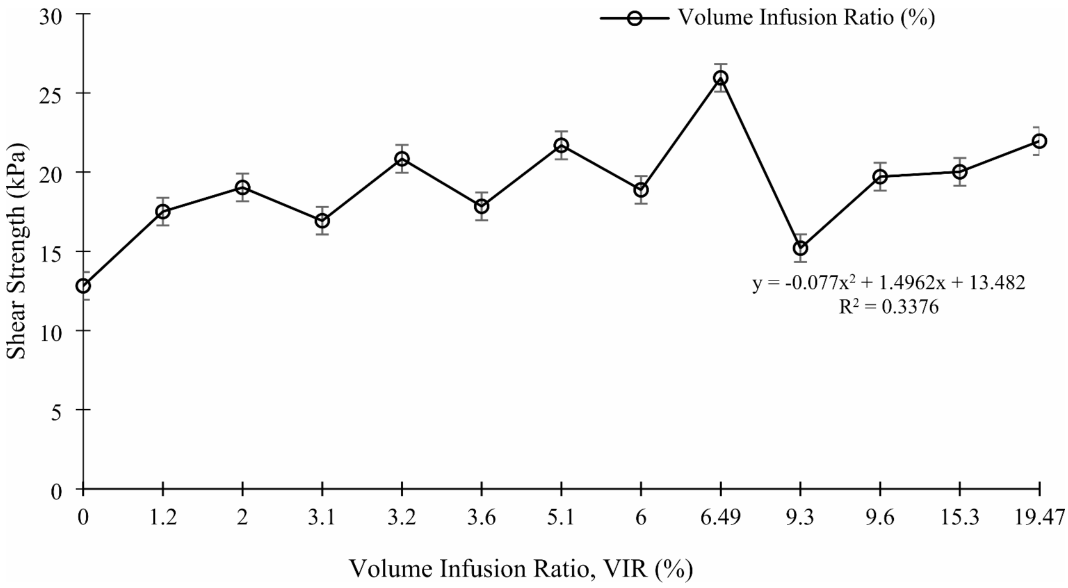


Fig. 11. Correlation between the volume infusion ratios, VIR with the strength of soft clay soil encapsulated POM column.

stiffness. For clustered encapsulated POM columns, the improvement in inferior shear strength can be ascribed to inadequate column depth, which restricts effective load transfer and distribution into the surrounding soil. Short columns provide minimal interaction surface, resulting in deficient frictional resistance and bonding, coupled with inadequate vertical confinement to counteract lateral soil movement.

Furthermore, the overlapping zones of influence from multiple short columns fail to reinforce the soil substantially. The shear resistance within the soil is contingent upon friction, particle interconnection, and contact linkage, with volume change behaviour and friction being influenced by particle density and intergranular contact forces. When the soil undergoes expansion, particle density decreases, diminishing resistance and shear stress, ultimately weakening the stress-stress relationship as interparticle bonds break upon cessation of volume change. As portrayed in Fig. 11, the R^2 values for the regression models were relatively low, indicating that only a small proportion of the variability in the strength parameters of soft clay soil can be attributed to the deployment of POM columns. Specifically, the R^2 value was 0.3376, meaning that just 33.76% of the variation in shear strength is explained by the use of POM columns in terms of VIR. These low R^2 values suggest that while POM columns may have some impact on the strength of soft clay soil, other factors not accounted for in the model likely play a significant role. This indicates that VIR alone may not be the primary factor influencing the strength improvement of soft clay soil.

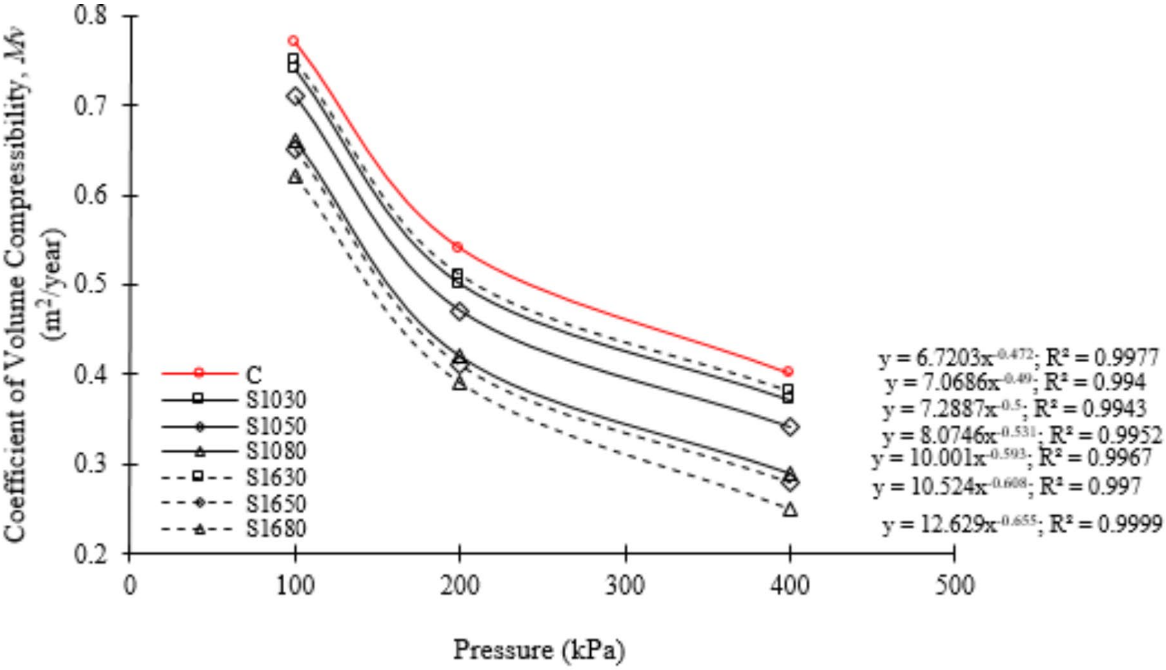
Influence of polyoxymethylene (POM) column deployment on the soft clay soil compressibility characteristics

Effect of polyoxymethylene (POM) column deployment on the coefficient of volume compressibility, Mv

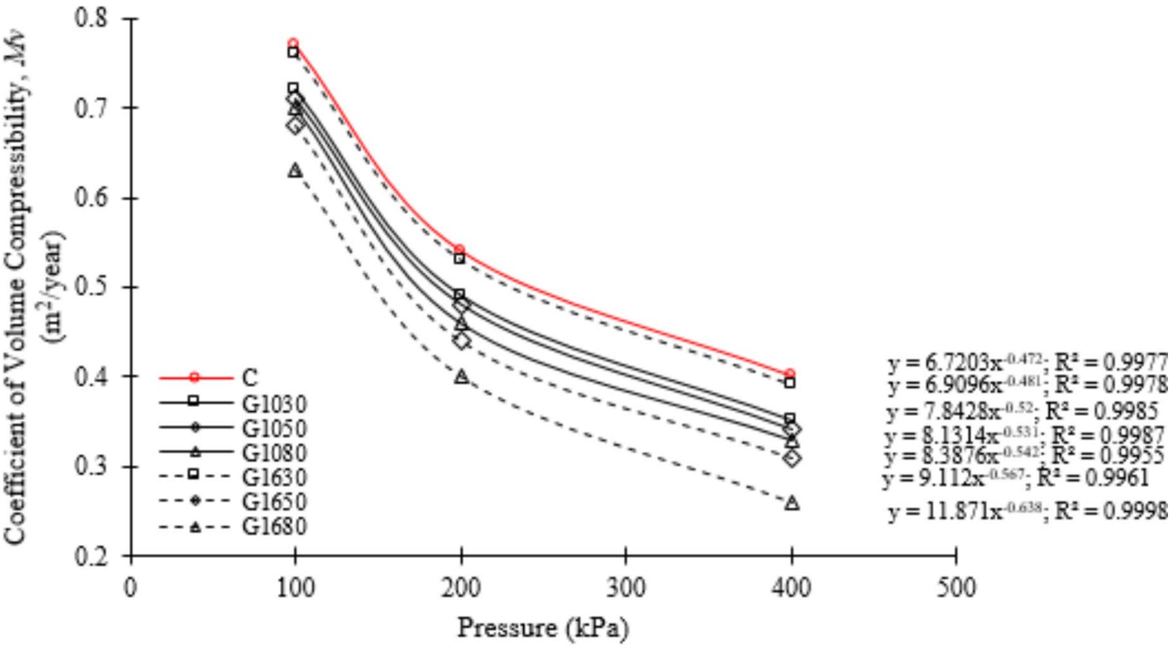
The Consolidated Isotropic Undrained (CIU) triaxial test assessed soft clay reinforced with individual and clustered encapsulated polyoxymethylene (POM) columns for compressibility. Figure 12(a) and (b) highlights the effect of various pressure (100, 200, and 400 kPa) on the coefficient of volume compressibility, m_v.

Based on the figure, it can be deduced that the increment in pressures resulted to the reduction of m_v for soft clay soil reinforced with 10 and 16 mm POM columns with a value of 0.74 m^2/MN, 0.50 m^2/MN, 0.37 m^2/MN; 0.71 m^2/MN, 0.47 m^2/MN, 0.34 m^2/MN; 0.66 m^2/MN, 0.42 m^2/MN, 0.29 m^2/MN (for individual encapsulated POM columns with 10 mm diameter with height of 30, 50, and 80 mm respectively), 0.75 m^2/MN, 0.51 m^2/MN, 0.38 m^2/MN; 0.65 m^2/MN, 0.41 m^2/MN, 0.28 m^2/MN; 0.62 m^2/MN, 0.39 m^2/MN, 0.25 m^2/MN (for individual encapsulated POM columns with 16 mm diameter with height of 30 mm, 50 mm, and 80 mm respectively), 0.72 m^2/MN, 0.49 m^2/MN, 0.35 m^2/MN; 0.71 m^2/MN, 0.48 m^2/MN, 0.34 m^2/MN; 0.70 m^2/MN, 0.46 m^2/MN, 0.33 m^2/MN (for clustered encapsulated POM columns with 10 mm diameter with height of 30, 50, and 80 mm respectively), and 0.76 m^2/MN, 0.53 m^2/MN, 039 m^2/MN; 0.68 m^2/MN, 0.44 m^2/MN, 0.31 m^2/MN; 0.63 m^2/MN, 0.40 m^2/MN, 0.26 m^2/MN (for clustered encapsulated POM columns with 16 mm diameter with height of 30, 50, and 80 mm respectively).

The coefficient of volume compressibility, m_v, diminishes as pressure increases due to soil structure densification at increased stress. At low pressures, soil particles are loosely packed and have a higher void ratio, making the soil more compressible. As pressure increases, the effective load on the soil forces particles to move closer together, lowering the void ratio and resulting in a denser soil structure. Because the soil particles are already closely packed, this densification reduces the possibility of further compression. As a result, the soil becomes less compressible, and m_v drops. This pattern reflects the non-linear connection between stress and



(a)



(b)

Fig. 12. Effect of pressure and coefficient of volume compressibility, m_v of: (**a**) individual encapsulated POM columns, and; (**b**) clustered encapsulated POM columns.

strain in soils, where high compressibility is the initial response to loading but decreases as the soil structure stabilizes under increasing pressures[37].

Figure 12(a) shows the effects and correlation of different pressures acting on individual encapsulated POM columns having a different column dimensions. Based on the figure, the regression analysis yielded R^2 values of 0.9977, 0.994, 0.9943, 0.9952, 0.9967, 0.997, and 0.9999. These results demonstrate that 99.77%, 99.40%, 99.43%, 99.52%, 99.67%, 99.70% and 99.99% of the variation in the coefficient of volume compressibility, m_v of soft clay soil is explained by the deployment of various dimensions of individual encapsulated POM columns under different pressures. On the other hand, Fig. 12(b) shows the effects and correlation of different pressures acting on clustered encapsulated POM columns having 10 and 16 mm column diameter with 30, 50, and 80 mm column depth. The regression analysis yielded R2 values of 0.9977, 0.9978, 0.9985, 0.9987, 0.9955, 0.9961, and 0.9998. These results also validate that 99.77%, 99.78%, 99.85%, 99.87%, 99.55%, 99.61% and 99.98% of the variation in the coefficient of volume compressibility, m_v of soft clay soil is explained by the deployment of various dimensions of clustered encapsulated POM columns under different pressures. The high R^2 values indicate a strong relationship between the implementation of POM columns and the reduction in coefficient of volume compressibility, m_v value, thus validating the effectiveness of this soil improvement technique.

Effect of polyoxymethylene (POM) column deployment on the coefficient of consolidation, Cv

Based on Fig. 13(a) and (b), the coefficient of consolidation, c_v determined at a pressures of 100, 200, and 400 kPa at various dimensions of individual and clustered encapsulated POM columns are 298.22 m^2/year, 318.83 m^2/year, 345.36 m^2/year; 387.07 m^2/year, 407.68 m^2/year, 434.21 m^2/year; 361.38 m^2/year, 381.99 m^2/year, 408.52 m^2/year (for individual encapsulated POM columns with 10 mm diameter with height of 30, 50, and 80 mm respectively), 283.11 m^2/year, 303.72 m^2/year, 330.25 m^2/year; 371.50 m^2/year, 392.11 m^2/year, 418.62 m^2/year; 418.12 m^2/year, 438.72 m^2/year, 465.26 m^2/year (for individual encapsulated POM columns with 16 mm diameter with height of 30 mm, 50 mm, and 80 mm respectively), 318.96 m^2/year, 339.57 m^2/year, 36,610 m^2/year; 329.94 m^2/year, 350.55 m^2/year, 377.08 m^2/year; 324.29 m^2/year, 344.90 m^2/year, 371.43 m^2/year (for clustered encapsulated POM columns with 10 mm diameter with height of 30, 50, and 80 mm respectively), and 272.75 m^2/year, 293.36 m^2/year, 319.89 m^2/year; 340.53 m^2/year, 36.14 m^2/year, 387.67 m^2/year; 402.46 m^2/year, 423.07 m^2/year, 449.60 m^2/year (for clustered encapsulated POM columns with 16 mm diameter with height of 30, 50, and 80 mm respectively). The results justify that the pressures are positively related to the c_v value, as the increment in the pressures also resulted to the augmentation in the c_v value.

Many factors can enhance the coefficient of variation *(c_v)* in POM columns supplemented with soft clay soil. Due to POM columns' reinforcement, the soil-column system is stiffer and can sustain more weight. Additionally, they advocate for a streamlined and consistent consolidation process. As vertical drains, these columns shorten drainage routes and accelerate pore water pressure dissipation. A less compressible soil structure results from improved drainage. As well as improving particle rearrangement and consolidation, POM columns reduce void ratios and stabilise soil. Higher coefficient of consolidation *(c_v)* values imply faster consolidation, while lower modulus of volume compressibility *(m_v)* values suggest less compressibility and improved soil strength due to the combined impacts. This study agrees with Zaini Hasan[37] and Nazari[38].

Figure 13(a) and 13(b) show how pressures affect individual and combination encapsulated POM columns of different diameters. The figure's regression analysis showed R^2 values of 0.9862 for all samples using individual or grouped encapsulated POM columns. Encapsulated POM column widths at varying pressures explain 98.62% of soft clay soil coefficient of consolidation *(c_v)* variance. High R^2 results suggest that POM columns improve the coefficient of consolidation, c_v value, proving this soil development approach works.

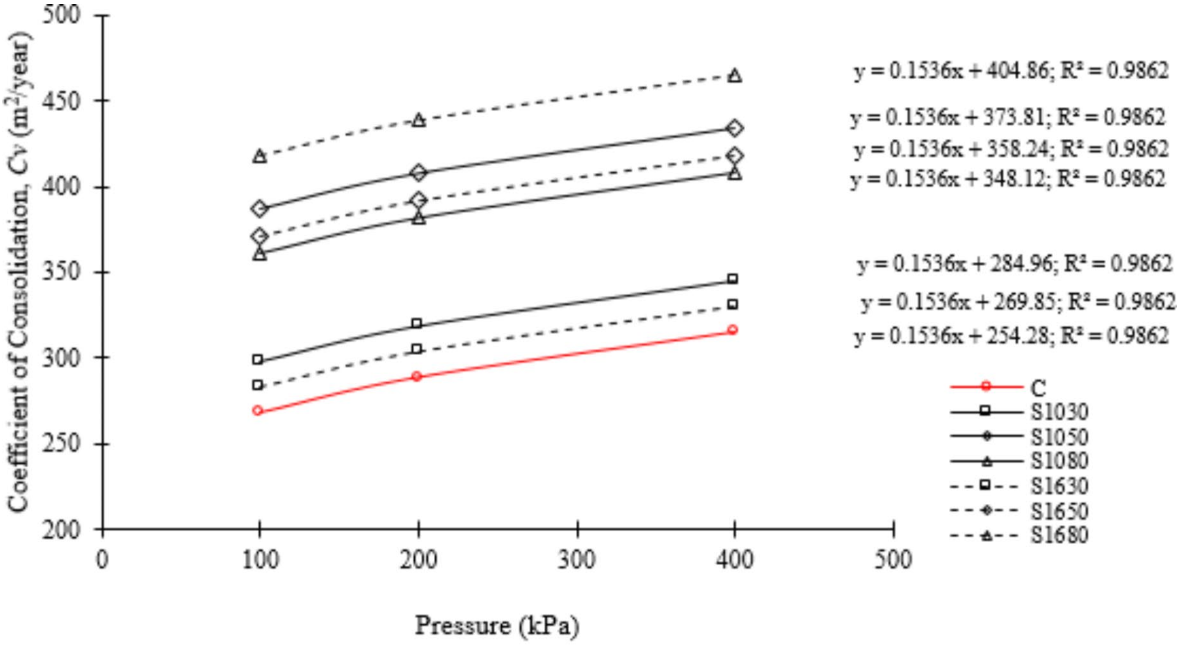
Influence of polyoxymethylene (POM) column deployment on the soft clay soil cohesion and friction angle

The CIU triaxial test assessed soft clay strength using solitary and clustered encapsulated polyoxymethylene (POM) columns. This extensive investigation tested three samples at 100, 200, and 400 kPa confining pressures to determine penetration. Comprehensive testing was done to assess the effective shear stress characteristics of soft clay soil strengthened with POM columns of various diameters. Key parameters include depth penetration ratio (DPR), substitution area ratio (SAR), volume infusion ratio (VIR), column aspect ratio (CAR), cohesiveness, and friction angle. Table 4 lists these. The soft clay strengthened with encapsulated POM columns has larger effective cohesiveness than the reference sample. Effective friction angles improved significantly over the unreinforced sample. Encapsulated POM columns may significantly boost shear strength in soft clay, proving this reinforcement technology's geotechnical potential.

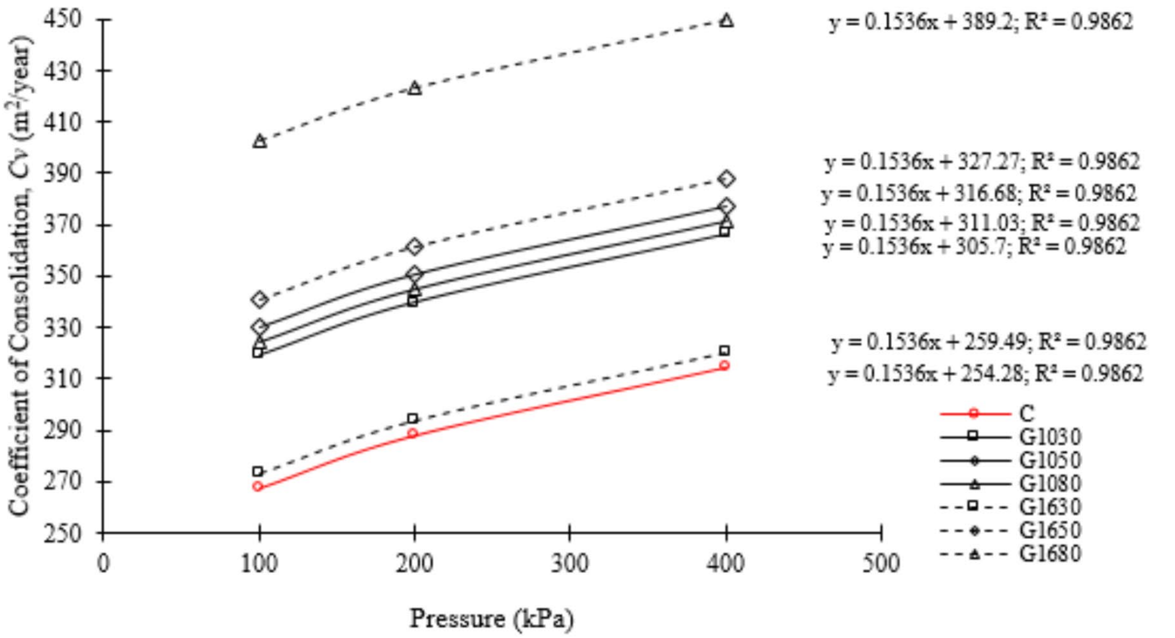
The cohesion of the soft clay soil's reference sample was 12.63 kPa. The cohesion values notably increased upon reinforcement with individual encapsulated polyoxymethylene (POM) columns. For instance, with a 10 mm diameter column and varying heights of 30, 50, and 80 mm, the cohesion values escalated to 13.73 kPa, 18.33 kPa, and 23.43 kPa, respectively. Similarly, for an individual 16 mm diameter column, the cohesion values were measured at 13.73 kPa, 23.83 kPa, and 25.03 kPa for the corresponding heights. Clustered column configurations with 10 mm and 16 mm diameter columns also displayed enhanced cohesion values compared to the control. Notably, the maximum cohesion value documented was 25.03 kPa for sample S1680, while the least was 13.23 kPa for sample G1630. The optimal cohesion values for individual and clustered encapsulated POM columns were consistently attained at a DPR of 0.8.

Moreover, as indicated in Table 5, the data revealed higher confining pressures attributed to improved cohesion values in the reinforced soil-POM column than the reference specimen. These significant differences in cohesion highlight the efficacy of POM column reinforcement in enhancing the bonding force between soil molecules. Cohesion increases resulting in stronger bonding within the soil matrix[39–44]. Rezaie et al.[30] observed that granular columns increased soil cohesion, and our results confirmed this. This study reveals that POM columns of different sizes and topologies improve soil particle interaction and cohesiveness.

Table 4 displays the control sample's 22.3° friction angle (φ°). In several cases, solitary and clustered encapsulated polyoxymethylene (POM) columns improved friction angles. Encapsulated POM columns of 10 mm diameter; 30, 50, and 80 mm depth had friction angles of 24.7°, 27.1°, and 27.9°. The friction angles for clustered encapsulated POM columns with the exact column diameters were 25.7°, 26.2°, and 27.6°. Greater friction angles were reported with 16 mm columns. Individual and clustered encapsulated POM columns had



(a)



(b)

Fig. 13. Correlation between the pressure and coefficient of consolidation, c_v of: (**a**) individual encapsulated POM columns, and; (**b**) clustered encapsulated POM columns.

angles of 24.5° to 29.4° and 23.7° to 28.4°, respectively. Samples G1630 and S1680 had friction angles of 23.7 and 29.4 degrees, respectively. Shear stress and normal effective stress are linked by the friction angle, which depicts the angle on Mohr's Circle at which shear failure occurs[45–52]. The study found that shear stress and typical effective stress increase friction angles. The occurrences given by Hasan et al.[28] support the importance of particle size in column material on reinforced clayey soil behaviour. This affects shear strength, friction angle, and stiffness[52–57]. The increased shear and effective normal stress from installing POM columns of varied

No. of column	Confining pressures (kPa)	Column dia. (mm)	Column depth (mm)	SAR	VIR	DPR	CAR	c (kPa)	Φ (°)
	100								
0	200	0	0	0	0	0	0	12.63	22.3
	400								
	100								
1	200	10	30	4.00	1.20	0.3	3	13.73	24.7
	400								
	100								
1	200	10	50	4.00	2.00	0.5	5	18.33	27.1
	400								
	100								
1	200	10	80	4.00	3.20	0.8	8	23.43	27.9
	400								
	100								
1	200	16	30	10.24	3.10	0.3	1.88	13.73	24.5
	400								
	100								
1	200	16	50	10.24	5.10	0.5	3.13	23.83	28.2
	400								
	100								
1	200	16	80	10.24	6.49	0.8	5	25.03	29.4
	400								
	100								
3	200	10	30	12.00	3.60	0.3	3	17.63	25.7
	400								
	100								
3	200	10	50	12.00	6.00	0.5	5	17.83	26.2
	400								
	100								
3	200	10	80	12.00	9.60	0.8	8	20.73	27.6
	400								
	100								
3	200	16	30	30.72	9.30	0.3	1.88	13.23	23.7
	400								
	100								
3	200	16	50	30.72	15.30	0.5	3.13	20.73	27.7
	400								
	100								
3	200	16	80	30.72	19.47	0.8	5	24.73	28.4
	400								

Table 4. Empirical value of cohesion and friction angle of soft clay soil and reinforced soft clay soil with individual and clustered encapsuled POM columns. SAR, Substitute Area Ratio; VIR, Volume Infusion Ratio; DPR, Depth Penetration Ratio; CAR, Column Aspect Ratio; C, Cohesion; and, Φ, Friction Angle.

diameters and configurations in this study altered the friction angle. These statistics show that reinforced soil friction angle is sensitive to effective normal stress and shear stress.

Statistical analysis and establishment of shear strength prediction model of reinforced soft clay soil with encapsulated POM columns

A one-way ANOVA test examined eight essential parameters: column number, diameter, depth, effective confining pressures (CP), depth penetration ratio (DPR), volume infusion ratio (VIR), and column aspect ratio. The study found significant differences across parameters at a significance level of $P < 0.05$. We used Fisher's LSD test to identify the variables causing these shifts. Table 5 shows ANOVA and LSD results. In 27 LSD analyses, 16 supported the null hypothesis (H_0) and 11 denied it, a statistically significant difference. Confining pressures, number of columns with diameter, and column diameter with depth differed significantly. These variances were quantified using mean differences of 36.09 to 233.3 and LSD values of 20.41. This LSD-based mean separation approach follows Zaini et al.[33] conventional process.

Mean	Absolute mean difference		Remark
	Mean diff.	Value	
$\bar{x}_1$	$\bar{x}_1$-$\bar{x}_3$	47.38	Difference is significant at $p=0.05$, LSD = 20.41
	$\bar{x}_1$-$\bar{x}_8$	231.48	
$\bar{x}_2$	$\bar{x}_2$-$\bar{x}_3$	37.23	
	$\bar{x}_2$-$\bar{x}_8$	221.33	
$\bar{x}_3$	$\bar{x}_3$-$\bar{x}_4$	36.09	
	$\bar{x}_3$-$\bar{x}_5$	48.49	
	$\bar{x}_3$-$\bar{x}_6$	43.23	
	$\bar{x}_3$-$\bar{x}_7$	38.69	
	$\bar{x}_3$-$\bar{x}_8$	184.10	
$\bar{x}_4$	$\bar{x}_4$-$\bar{x}_8$	220.19	
$\bar{x}_5$	$\bar{x}_5$-$\bar{x}_8$	232.59	
$\bar{x}_6$	$\bar{x}_6$-$\bar{x}_8$	233.33	

Table 5. Identification of specific parameters contributing to the enhancement of strength through LSD. $\bar{x}_1$, Number of column; $\bar{x}_2$, Column Diameter; $\bar{x}_3$, Column Depth; $\bar{x}_4$, Substitute Area Ratio (SAR); $\bar{x}_5$, Depth Penetration Ratio (DPR); $\bar{x}_6$, Column Aspect Ratio (CAR); $\bar{x}_7$, Volume Infusion Ratio (VIR); $\bar{x}_8$, Confining Pressures (CP).

Parameter	NC	CD	Cd	SAR	DPR	CAR	VIR	CP
NC	1.00							
CD	0.37	1.00						
CH	0.28	0.45	1.00					
SAR	0.76	0.66	0.22	1.00				
DPR	0.39	0.62	0.95	0.30	1.00			
CAR	0.32	0.16	0.78	0.08	0.83	1.00		
VIR	0.72	0.62	0.41	0.95	0.43	0.04	1.00	
CP	3.72×10^{-17}	2.1×10^{-17}	4.6×10^{-17}	1.82×10^{-17}	0	3.4×10^{-17}	1.1×10^{-17}	1.00

Table 6. Evaluation of the correlation observed parameters based on Pearson's correlation coefficient. NC, Number of column; CD, Column diameter; Cd, Column Depth; CP, Confining pressure; SAR, Substitute Area Ratio; DPR, Depth Penetration Ratio; CAR, Column Aspect Ratio; VIR, Volume Infusion Ratio.

Table 6 provides the outcomes of Pearson's correlation coefficient analysis, which explored the interrelationships among the variables considered in this study. A correlation coefficients below 0.4 denote a weak relationship, while those exceeding 0.4 signify a strong relationship; a correlation coefficient of zero indicates no relationship[56–60]. The analysis reveals a robust correlation between the number of columns (NC) and both the substitute area ratio (SAR) and volume infusion ratio (VIR), with correlation coefficients of 0.76 and 0.72, respectively. Conversely, confining pressures exhibit almost no relationship with other variables. Weak correlations are observed for column diameter (CD), column depth (Cd), depth penetration (DPR), and column aspect ratio (CAR), as their correlation coefficients fall below 0.40. Furthermore, column depth (Cd) displays strong correlations with DPR ($r=0.95$) and moderate correlations with CAR ($r=0.78$) and VIR ($r=0.41$). Additionally, Cd exhibits weak correlations with the substitute area ratio (SAR) and confining pressures (CP). Notably, SAR and VIR demonstrate a strong correlation ($r=0.95$) with each other but weak correlations with DPR, CAR, and CP. Moreover, DPR strongly correlates with CAR ($r=0.83$) and VIR ($r=0.43$). However, it demonstrates a weak correlation with SAR. Conversely, there is no discernible correlation between the NC, CD, Cd, SAR, DPR, CAR, VIR, and CP variables. These correlation analyses provide valuable insights into the relationships among the parameters considered in this study, facilitating a comprehensive understanding of their interplay in soft clay reinforcement with encapsulated POM columns[61,62].

Multiple regression analysis was used to develop a mathematical equation and model that described the link between the eight (8) controllable variables (NC, CD, Cd, SAR, DPR, CAR, VIR, and CP) and strength. A prediction model was created to forecast the strength value (see Table 7), and the best prediction model was chosen based on the multiple regression analysis that resulted in the greatest adjusted R^2 value to predict the strength of the soft clay sample. The study includes a total of 93 regression analyses. From the 93 analyses performed, 67 were eliminated because the adjusted R^2 value was less than 0.2, indicating a weak relationship between the variables analyzed. The remaining 26 analyses were chosen and tabulated in Table 7 based on the R^2 value that contributed to the strongest relationship between the variables studied.

Regression equation	F-Sig.	R^2	Adjusted R^2
$SS = 30.07 + 0.55x_8$	8.03×10^{-28}	0.9705	0.9504
$SS = 30.56 - 0.31x_1 + 0.66x_8$	4.44×10^{-26}	0.9705	0.9494
$SS = 19.16 + 0.73x_2 + 0.66x_8$	3.21×10^{-27}	0.9761	0.9552
$SS = 15.02 + 0.20x_3 + 0.66x_8$	9.66×10^{-29}	0.9812	0.9607
$SS = 28.63 - 0.14x_4 + 0.66x_8$	3.54×10^{-26}	0.9711	0.9500
$SS = 13.12 + 14.40x_5 + 0.66x_8$	8.67×10^{-29}	0.9812	0.9607
$SS = 14.30 + 2.21x_6 + 0.66x_8$	3.38×10^{-29}	0.9824	0.9620
$SS = 22.56 - 0.16x_7 + 0.66x_8$	3.34×10^{-26}	0.9710	0.9499
$SS = 20.57 - 1.87x_1 + 1.00x_2 + 0.66x_8$	2.69×10^{-26}	0.9775	0.9558
$SS = 16.32 + 0.20x_2 + 0.18x_3 + 0.66x_8$	2.71×10^{-27}	0.9814	0.9600
$SS = 18.00 + 0.22x_3 - 0.30x_4 + 0.66x_8$	2.44×10^{-28}	0.9836	0.9635
$SS = 18.00 - 0.30x_4 + 22.12x_5 + 0.66x_8$	2.14×10^{-28}	0.9846	0.9535
$SS = 17.32 + 8.88x_5 + 1.41x_6 + 0.66x_8$	9.77×10^{-28}	0.9830	0.9518
$SS = 19.14 + 2.14x_6 - 0.16x_7 + 0.66x_8$	7.43×10^{-28}	0.9832	0.9519
$SS = 18.12 - 2.69x_1 + 0.34x_2 + 0.21x_3 + 0.66x_8$	7.50×10^{-27}	0.9844	0.9625
$SS = 17.17 + 1.16x_2 + 0.14x_3 - 0.55x_4 + 0.66x_8$	3.14×10^{-28}	0.9887	0.9673
$SS = 17.42 + 0.18x_3 - 0.25x_4 + 0.41x_5 + 0.66x_8$	3.11×10^{-27}	0.9847	0.9334
$SS = 17.42 - 0.25x_4 + 19.43x_5 + 0.41x_6 + 0.66x_8$	5.13×10^{-27}	0.9847	0.9628
$SS = 17.13 + 29.43x_5 - 0.29x_6 - 0.52x_7 + 0.66x_8$	3.33×10^{-27}	0.9869	0.9655
$SS = 15.72 + 2.02x_1 + 1.44x_2 + 0.11x_3 - 0.77x_4 + 0.66x_8$	4.50×10^{-27}	0.9802	0.9672
$SS = 8.89 - 5.11x_1 + 3.37x_2 - 0.84x_3 - 0.69x_4 + 17.69x_5 + 8.61x_6 + 1.07x_7 + 0.66x_8$	3.28×10^{-27}	0.9960	0.9819
$SS = 8.72 + 2.38x_2 - 0.34x_3 - 0.46x_4 + +19.70x_5 + 4.17x_6 + 0.66x_8$	4.02×10^{-29}	0.9938	0.9722
$SS = 11.26 + 0.34x_3 + 0.78x_4 - 0.31x_6 - 1.37x_7 + 0.66x_8$	4.05×10^{-27}	0.9801	0.9779
$SS = 11.26 + 0.81x_4 + 33.95x_5 - 0.31x_6 - 1.37x_7 + 0.66x_8$	4.36×10^{-27}	0.9811	0.9811
$SS = 9.11 - 4.72x_1 + 2.41x_2 - 0.51x_3 + 0.09x_4 + 26.59x_5 + 6.42x_6 + 0.66x_8$	2.61×10^{-28}	0.9964	0.9725
$SS = 8.52 + 3.16x_2 - 0.59x_3 - 1.13x_4 + 33.95x_5 + 5.79x_6 + 0.83x_7 + 0.66x_8$	8.20×10^{-28}	0.9953	0.9713

Table 7. Determination of the optimum regression model for predicting shear strength using regression analysis. SS, Shear Strength; F-sig, F-Test; R^2, Correlation of Determination; x_1, Number of Columns; x_2, Column Diameter; x_3, Column Depth; x_4, Substitute Area Ratio (SAR); x_5, Depth Penetration Ratio (DPR); x_6, Column Aspect Ratio (CAR); x_7, Volume Indusion Ratio (VIR); x_8, Confining Pressure (CP).

Regression equation	$C_p = p + 1$	Calculated C_p
$SS = 8.52 + 3.16x_2 - 0.59x_3 - 1.13x_4 + 33.95x_5 + 5.79x_6 + 0.83x_7 + 0.66x_8$	8	12.1604
$SS = 8.89 - 5.11x_1 + 3.37x_2 - 0.84x_3 - 0.69x_4 + 17.69x_5 + 8.61x_6 + 1.07x_7 + 0.66x_8$	9	9.9999
$SS = 9.11 - 4.72x_1 + 2.41x_2 - 0.51x_3 + 0.09x_4 - 26.59x_5 + 6.42x_6 + 0.66x_8$	8	9.6580
$SS = 8.72 + 2.38x_2 - 0.34x_3 - 0.46x_4 + 19.70x_5 + 4.17x_6 - 0.66x_8$	7	11.2655

Table 8. Selection of the optimum prediction model for soft clay soil strength using Mallow's C_p criterion. SS, Shear Strength; F-sig, F-Test; R^2, Correlation of Determination; x_1, Number of Columns; x_2, Column Diameter; x_3, Column Depth; x_4, Substitute Area Ratio (SAR); x_5, Depth Penetration Ratio (DPR); x_6, Column Aspect Ratio (CAR); x_7, Volume Indusion Ratio (VIR); x_8, Confining Pressure (CP).

Regression analysis employs Mallow's C_p criterion, a statistical technique, to assess a model's predictive power and select the optimal subset of predictor variables, thereby avoiding overfitting, which occurs when a model is overly complex and captures noise or arbitrary oscillations in the data, resulting in a model's poor ability to generalize to new data. Furthermore, Mallow's C_p criterion seeks to identify a model that achieves a balance between goodness of fit and model complexity. Lower C_p values indicate higher prediction accuracy and less model complexity. Based on the 26 regression analyses completed, four (4) analyses were chosen for final review to determine the best prediction model in the study. The four (4) analyses were chosen based on the simplified model (estimated C_p) that is most similar to $C_p = p + 1$. Table 8 provides the best prediction model for soft clay soil strength using Mallow's C_p criterion.

Table 8 portrays that all regression equations are valid for regression analysis, with significant values excluded for H_0 at $p < 0.05$. Using the equation, each model in Table 8 can best describe around 85.0% of the data. As a result, additional analyses were undertaken to pick the best predictions from the shear strength model. With an adjusted R^2 of 0.9819, this equation can explain 98.19% of the data. Based on the updated R^2, the best prediction model for shear strength is shown below.

$$SS = 8.89 - 5.11x_1 + 3.37x_2 - 0.84x_3 - 0.69x_4 + 17.69x_5 + 8.61x_6 + 1.07x_7 + 0.66x_8 \tag{2}$$

where SS is the shear strength, x_1 is NC, x_2 is CD, x_3 is Cd, x_4 is SAR, x_5 is DPR, x_6 is CAR, x_7 is VIR, and x_8 is CP. On the basis of Eq. (2), the examination concluded that the shear strength is firmly affected by NC, CD, Cd, SAR, DPR, CAR, VIR, and CP. Furthermore, to validate the model, Mallow's C_p criterion was used as tabulated in Table 8. To determine the best prediction model, the value of the calculated Cp must be precisely or approximately equal to $C_p = p + 1$. Hence, it can be validated that among the four (4) listed models, Eq. (2) has the most precise and approximate value to its $C_p = p + 1$ value (calculated $C_p = 9.9999$ which is close to $C_p = p + 1 = 9$). Hence, a conclusion can be inferred from this model, indicating that the alterations NC, CD, Cd, SAR, DPR, CAR, VIR, and CP can lead to the enhancement of strength of the soft clay soil.

Conclusions

This investigation explored the influence of encapsulated POM columns on strengthening soft clay soil. Based on the conducted research, the following conclusions can be inferred:

(a) Utilizing individual and clustered encapsulated POM columns at different dimensions can alter the geotechnical properties of the soft clay soil.
(b) Utilizing individual and clustered encapsulated POM columns at different dimensions can improve the compressibility characteristics of the soft clay soil by increasing the value of the coefficient of consolidation and reducing the value of the volume compressibility.
(c) Using individual and clustered encapsulated POM columns at different diameters can strengthen the unconfined compressive strength and enhance the shear strength characteristics of the soft clay soil.
(d) Pursuant to the statistical analysis, there are noticeable variations among all the parameters tested at a significance level of $p < 0.05$. These differences are correlated with the enhancement of the strength of the soft clay soil, which is reinforced by both individual and clustered encapsulated POM columns. Besides, by employing regression analysis and Mallow's Cp Criterion, the establishment of the prediction model for estimating the shear strength of reinforced soft clay soil with encapsulated POM columns are accurately estblished.
(e) Following the results of this study, it is suggested that professionals use individual and clustered encapsulated POM columns with a diameter of 16 mm and a height of 80 mm to improve the functionality of soft clay soil in building applications. This design has shown the ability to offer a significant increase in ground improvement of up to 102.42%.

While the laboratory tests conducted in this study demonstrate significant improvements in the mechanical properties of soft clay soil reinforced with Polyoxymethylene (POM) columns, it is important to consider the potential scale effects when applying these findings to full-scale engineering projects. The behavior of soil can vary significantly between small-scale laboratory conditions and large-scale field applications due to differences in stress distribution, boundary conditions, and other factors. To validate the applicability of these results, it is recommended to perform finite element modeling (FEM) to simulate full-scale scenarios based on the laboratory findings. Additionally, conducting larger-scale physical tests would help bridge the gap between small-scale experiments and real-world applications. Further research in this area is necessary to ensure that the observed improvements in soil properties can be reliably replicated in full-scale projects.

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Received: 11 July 2024; Accepted: 16 September 2024
Published online: 29 September 2024

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Acknowledgements
The authors extend their appreciation to Prince Sattam bin Abdulaziz University for funding this research work through the project number (PSAU/2023/01/25611).

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Declarations

Competing interests
The authors declare no competing interests.

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