

COMPACTION OPTIMIZATION OF SILTY SANDS USING FACTORIAL DESIGN AND REGRESSION MODELING IN PATHUM THANI

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ABSTRACT: This study establishes an optimization-based framework for improving the compaction performance of natural and modified silty sands widely used in earthwork applications in Pathum Thani, Thailand. A $3 \times 3 \times 3$ full-factorial design comprising 27 Modified Proctor tests was conducted on natural silty sand (SM-N), cement-modified silty sand (SM-C), and polymer-modified silty sand (SM-P). The results reveal clear soil-dependent compaction behavior, with maximum dry density (MDD) values of 1.81 g/cm^3 for SM-N, 1.65 g/cm^3 for SM-C, and 1.788 g/cm^3 for SM-P under their respective optimal conditions. The highest densities were consistently achieved at $1.5\times$ compaction energy, while optimum moisture levels varied by soil type OMC for SM-N and SM-P, and $\text{OMC} + 2\%$ for SM-C. Increasing compaction effort from $0.5\times$ to $1.5\times$ yielded up to a 12.4% improvement in MDD, whereas moisture deviations of $\pm 2\%$ from OMC resulted in 4–9% reductions in density depending on modification type. ANOVA confirmed that all main factors and interaction terms were statistically significant ($p < 0.05$), emphasizing the multi-variable nature of silty sand compaction. A second-order regression model demonstrated strong predictive accuracy ($R^2 = 0.968$), enabling reliable estimation of density across varying field conditions. The integration of factorial analysis and predictive modeling produced a soil-specific compaction optimization matrix that highlights the superior densification potential of polymer-modified silty sand and the moisture-sensitive behavior of cement-treated material. Overall, the proposed framework provides a systematic, data-driven alternative to conventional trial-based compaction practices and enhances earthwork reliability in moisture-sensitive silty sand deposits.

Keywords: Soil compaction, Maximum Dry Density, Optimization, Factorial design, regression modeling.

1. INTRODUCTION

Soil compaction is one of the most important processes in geotechnical engineering because it directly influences the stability, load-bearing capacity, stiffness, permeability, and long-term performance of embankments, subgrades, foundations, and other earth structures. Proper compaction increases soil density by reducing air voids, thereby enhancing shear strength and minimizing excessive settlement and deformation under service loads. Achieving an adequate Maximum Dry Density (MDD) at or near the appropriate Optimum Moisture Content (OMC) is therefore a fundamental objective in both laboratory mix design and field quality control for transportation and infrastructure projects. Numerous documented failures of pavement systems, road embankments, and earthworks have been attributed to insufficient compaction energy or poor moisture control during construction, particularly in regions dominated by moisture-sensitive soils [1,2]. These failures underscore the critical need for systematic research on soil compaction behavior under varying material conditions and construction parameters.

In tropical and monsoon-influenced regions such as Central Thailand, compaction control presents

additional challenges due to pronounced seasonal rainfall, fluctuating groundwater levels, and rapid changes in in situ moisture conditions. Silty sands are widely distributed in this region and are frequently used in road construction, embankment fills, and building platforms because of their availability, ease of excavation, and relatively favorable workability. However, the compaction response of silty sands is highly sensitive to moisture fluctuation, fines content, and soil fabric. Small deviations from the optimum moisture condition can lead to significant reductions in achievable dry density and stiffness, resulting in inconsistent field performance and increased susceptibility to post-construction settlement and distress [3–6]. These issues are particularly critical in rapidly developing areas such as Pathum Thani Province, where accelerated construction schedules demand reliable and repeatable compaction guidelines.

To mitigate these limitations, soil modification techniques have been increasingly adopted in earthwork practice to improve the mechanical behavior and durability of silty sands. Cement-treated silty sands have been widely used due to their ability to enhance particle bonding and dry density through hydration and cementation reactions [3,5]. More

recently, polymer-modified soils have attracted growing attention because polymer additives can improve particle interlock, flexibility, and resistance to moisture-induced degradation while requiring relatively low additive contents [4]. Several studies have reported that polymer-modified silty sands exhibit superior compaction efficiency and higher achievable densities compared to untreated or cement-treated materials under controlled moisture conditions. Despite their increasing application in practice, the combined influence of soil modification type, moisture condition, and compaction effort on MDD has not yet been comprehensively quantified for local silty sands in Thailand [7].

Previous research has examined the individual effects of compaction energy [5], soil stabilization mechanisms [3], and moisture variation on soil density and strength characteristics [6,8]. However, most existing studies evaluate these parameters independently, often relying on single-factor experimental approaches. Such methods provide useful baseline insights but fail to capture the nonlinear and interactive nature of soil compaction mechanisms. Only a limited number of studies employ factorial experimental designs or statistical interaction analyses to investigate how soil type, moisture content, and compaction energy collectively influence Maximum Dry Density [9]. In parallel, regression-based and data-driven techniques have gained increasing attention for predicting soil behavior and compaction performance [10,11]. Nevertheless, predictive models specifically developed for optimizing the compaction of natural and modified silty sands using systematically designed factorial experiments remain scarce.

In practical field operations, compaction control still relies heavily on repeated laboratory Proctor testing and empirical trial-and-error procedures [12]. These approaches are time-consuming, costly, and often impractical under rapidly changing site conditions, particularly in regions with high moisture variability. Data-driven optimization frameworks that integrate experimental results with statistical modeling offer a promising alternative by enabling engineers to estimate achievable dry density, assess sensitivity to moisture deviation, and select appropriate compaction energy levels without excessive testing. However, such integrated frameworks have not been widely developed or validated for silty sands commonly encountered in Central Thailand.

Therefore, this study focuses on the optimization of silty sand compaction by integrating a $3 \times 3 \times 3$ full-factorial experimental design with second-order regression modeling to quantify both main effects and interaction effects among soil type, moisture content, and compaction effort. Natural silty sand, cement-modified silty sand, and polymer-modified silty sand representative of materials used in Pathum Thani,

Thailand, are systematically evaluated under controlled laboratory conditions. The objectives of the study are to: (1) systematically evaluate the compaction behavior of natural, cement-modified, and polymer-modified silty sands; (2) develop a robust predictive model for estimating Maximum Dry Density under varying moisture and energy conditions; and (3) propose an optimized compaction strategy applicable to field conditions in Pathum Thani. The findings provide new insights into the compaction behavior of modified silty sands and offer practical guidance for engineers working with moisture-sensitive soils.

2. RESEARCH SIGNIFICANCE

This study presents an original and integrated framework for optimizing the compaction behavior of silty sands by simultaneously considering soil modification, moisture condition, and compaction energy. While previous studies have emphasized the importance of multi-variable interactions in compaction performance, most investigations remain limited to single-factor or partially coupled analyses [5–9]. The novelty of this research lies in the application of a full-factorial experimental design combined with second-order regression modeling to quantify both main and interaction effects for natural, cement-modified, and polymer-modified silty sands. Furthermore, the proposed compaction optimization matrix translates statistical outcomes into practical engineering guidance, addressing the need for data-driven and cost-effective compaction control tools highlighted in recent geotechnical and GEOMATE studies [10–13], particularly for moisture-sensitive silty sands in Pathum Thani, Thailand, as summarized in Table 1.

3. METHODOLOGY

3.1 Experimental Materials

Three types of silty sand were selected to represent natural and modified soil conditions commonly encountered in construction projects within Pathum Thani, Thailand. Each soil type was prepared following standardized laboratory procedures, and their physical and chemical characteristics are summarized in Table 2.

SM-N (Natural Silty Sand): Untreated soil containing predominantly sand-sized particles with moderate silt content and minimal clay. This soil is non-plastic, indicating limited cohesive behavior.

SM-C (Cement-Modified Silty Sand): Produced by mixing natural silty sand with 5% Portland cement by dry weight. Cement introduces hydration reactions that increase bonding, density, and moisture sensitivity, consistent with previous findings on artificially cemented soils [3].

Table 1 Summary of Literature Gaps from Previous Studies.

Reference	Soil Modification	Compaction Behavior	Moisture Influence	Energy Influence	Interaction Effects	Regression / ML Modeling
[3] Consoli et al.	Cemented soils	x	x	–	–	–
[4] Maher & Ho	Polymer/fiber modification	x	–	–	–	–
[5] Sariosseiri & Muhunthan	Cement treatment	x	x	–	–	–
[6] Estabragh et al.	–	x	x	–	–	–
[11] Zhang et al.	–	x	x	x	–	–
[14] Al-Ani & Al-Omari	–	x	–	x	–	–
[15] Kaya et al.	–	–	–	–	–	x
[16] Mir	–	–	–	–	–	x
This Study	x	x	x	x	x	x

SM-P (Polymer-Modified Silty Sand): Modified using 3% synthetic polymer, designed to improve workability, enhance particle bridging, and increase resistance to deformation. Polymer additives have been reported to enhance compaction behavior and structural stability in treated soils [4]. The grain size distribution and plasticity characteristics of the tested soils are presented in table 2. All soils were air-dried and passed through a 4.75-mm sieve prior to testing to ensure uniformity.

Table 2 Physical and Chemical Properties of Tested Soils

Soil Type	Modification Method	Grain Size Distribution (%)	Plasticity Index
SM-N	No modification	Sand: 65%, Silt: 30%, Clay: 5%	Non-plastic
SM-C	5% Portland cement	Sand: 60%, Silt: 30%, Clay: 10%	Low plasticity
SM-P	3% synthetic polymer	Sand: 62%, Silt: 28%, Clay: 10%	Medium plasticity

3.2 Experimental Variables

The experimental program was designed using a full-factorial framework (3 × 3 × 3) to systematically analyze how soil type, compaction energy, and moisture variation influence the Maximum Dry Density (MDD) of natural and modified silty sands. This approach enables the quantification of not only main effects but also second-order and three-way interaction effects, which are critical in complex geotechnical systems [9,11].

3.2.1 Independent Variables

Three independent variables, each at three levels, were considered. Soil type included natural silty sand (SM-N), cement-modified silty sand with 5% Portland cement (SM-C), and polymer-modified silty sand with 3% synthetic polymer (SM-P), representing untreated and commonly used soil modification methods in local construction practice. Compaction energy was varied relative to the Modified Proctor

standard (ASTM D1557) at 0.5×, 1.0×, and 1.5× to evaluate energy sensitivity and potential over-compaction effects [6]. Moisture condition was adjusted with respect to the Optimum Moisture Content (OMC) at OMC–2%, OMC, and OMC+2% to capture the influence of lubrication and pore-water effects on compactability [5].

3.2.2 Dependent Variable

The primary response measured in the study is: Maximum Dry Density (MDD) (g/cm³) This variable serves as the performance indicator for evaluating the compaction behavior of each soil–moisture–energy combination.

3.2.3 Factorial Structure

A full-factorial experimental design was adopted to investigate the combined effects of soil type, compaction energy, and moisture condition on Maximum Dry Density (MDD), as shown in Table 3. This approach allows comprehensive assessment of main and interaction effects for compaction optimization.

Table 3 Full-Factorial Experimental Design

Factor	Levels
Soil Type	SM-N, SM-C, SM-P
Compaction Energy	0.5×, 1.0×, 1.5×
Moisture	OMC–2%, OMC, OMC+2%

The design comprised three soil types (SM-N, SM-C, SM-P), three compaction energy levels (0.5×, 1.0×, and 1.5× Modified Proctor), and three moisture conditions (OMC–2%, OMC, and OMC+2%), resulting in 27 experimental runs covering all possible factor-level combinations. This factorial structure enables systematic evaluation of main and interaction effects among the investigated parameters, providing a robust framework for capturing the nonlinear and interdependent behavior of silty sand compaction and supporting subsequent optimization analysis [9].

3.3 Statistical Analysis

Statistical analysis was performed to assess the effects of soil type, compaction energy, and moisture condition, as well as their interactions, on Maximum Dry Density (MDD) using data from all 27 experimental runs.

3.3.1 Analysis of Variance (ANOVA)

A three-factor Analysis of Variance (ANOVA) was conducted to evaluate the effects of soil type, compaction energy, and moisture condition on Maximum Dry Density (MDD). The results show that all main factors significantly influence MDD ($p < 0.05$). Moreover, all two-way interactions and the three-way interaction are statistically significant, indicating strong interdependence among compaction parameters and confirming the suitability of a factorial-based analytical approach for assessing silty sand compaction behavior [5,6,9].

Table 4 A three-factor Analysis of Variance

Source	P-Value	Significance
Soil Type	0.000	Significant
Compaction Effort	0.000	Significant
Moisture Content	0.000	Significant
Soil Type × Compaction Effort	0.000	Significant
Soil Type × Moisture Content	0.005	Significant
Compaction Effort × Moisture Content	0.000	Significant
Soil Type × Compaction Effort × Moisture Content	0.002	Significant

3.3.2 Regression Model

(1) Model Structure

A regression-based modeling approach was adopted to quantify the nonlinear compaction behavior of natural and modified silty sands under varying compaction energy and moisture conditions. To represent the factorial nature of the experimental design, a second-order polynomial model was selected. The general structure of the regression model is presented in Equation (1):

$$\begin{aligned}
 MDD = & \beta_0 + \beta_1 E + \beta_2 M + \beta_3 D_{SM-C} + \beta_4 D_{SM-N} \\
 & + \beta_5 E^2 + \beta_6 EM + \beta_7 E D_{SM-C} \\
 & + \beta_8 E D_{SM-N} + \beta_9 M^2 \\
 & + \beta_{10} M D_{SM-C} + \beta_{11} M D_{SM-N}
 \end{aligned}
 \tag{1}$$

Where

- E = Compaction Energy
- M = Moisture Condition
- S_N = Dummy variable for soil type SM-N
- S_C = Dummy variable for soil type SM-C
- S_P serves as the reference category ($S_N, S_C = 0$)

Equation (1) captures linear effects, quadratic curvature, and two-way interactions among energy, moisture, and soil type.

(2) Expanded Polynomial Model

Polynomial regression was applied using a second-order expansion, resulting in the fully expanded model presented in Equation (2). Although the expansion introduces dummy-squared and cross-dummy terms that are mathematically redundant for binary variables, these terms were retained to preserve the exact form of the predictive and optimization model.

$$\begin{aligned}
 MDD_{pred} = & 1.7539 + 0.0600E - 0.0380M \\
 & - 0.0220D_{SM-C} - 0.1536D_{SM-N} \\
 & - 0.0074E^2 - 0.0008EM \\
 & + 0.0150ED_{SM-N} - 0.0988M^2 \\
 & - 0.0087MD_{SM-C} \\
 & + 0.0173MD_{SM-N}
 \end{aligned}
 \tag{2}$$

Equation (2) represents a second-order regression model fitted using coded compaction energy (E) and moisture condition (M), with SM-P as the reference soil. Dummy variables D_{SM-C} and D_{SM-N} denote cement-modified and natural silty sands, respectively. The coefficients are consistent with those reported in Table 5 and form the basis for subsequent prediction and optimization analyses.

(3) Model Estimation and Coefficients

Model parameters were estimated using ordinary least squares based on the full set of 27 experimental runs. The coefficients obtained from Equation (2) are presented in Table 5

Table 5. Regression Coefficients for the Second-Order MDD Prediction Model

Term	Symbol	β_i	Significance
Intercept	β_0	1.7539	Significance
Effort (linear)	β_1	+0.0600	Significance
Moisture (linear)	β_2	-0.0380	Significance
Dummy for SM-C	β_3	-0.0220	not significant
Dummy for SM-N	β_4	-0.1536	Significance
Effort ²	β_5	-0.0074	not significant
Effort × Moisture	β_6	-0.0008	not significant
Effort × SM-C	β_7	0.0000	not significant
Effort × SM-N	β_8	+0.0150	not significant
Moisture ²	β_9	-0.0988	Significance
Moisture × SM-C	β_{10}	-0.0087	not significant
Moisture × SM-N	β_{11}	+0.0173	not significant

Table 5 summarizes the regression coefficients of the expanded second-order model used to predict Maximum Dry Density (MDD) as a function of compaction energy, moisture condition, and soil type. Significant coefficients for energy (β_1) and moisture curvature (β_9) confirm their dominant influence on MDD, while soil-type dummy terms quantify the baseline density differences among SM-N, SM-C,

and SM-P. Interaction terms exhibit minor effects, consistent with the ANOVA results.

(4) Model Calibration and Performance

The predictive performance of the regression model was evaluated using standard statistical indicators. The model exhibits a high coefficient of determination ($R^2 = 0.968$), low mean absolute error ($MAE = 0.015 \text{ g/cm}^3$), and low root mean square error ($RMSE = 0.0188 \text{ g/cm}^3$), indicating strong predictive accuracy. As shown in Figure 1.

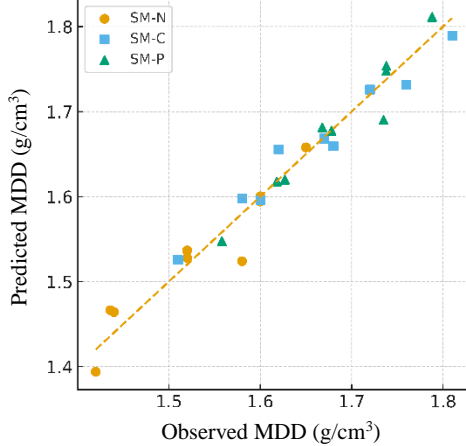


Fig. 1 Predicted versus observed Maximum Dry Density (MDD) from the regression model.

The predicted and observed MDD values closely follow the 1:1 reference line, confirming that the model effectively captures the underlying compaction behavior. The integration of ANOVA and regression modeling provides a statistically robust basis for subsequent compaction optimization.

(5) Residual and Diagnostic Analysis

Residual diagnostics (Figure 2) confirm the statistical adequacy of the regression model, demonstrating that it reliably captures the dominant effects of compaction energy, optimum moisture behavior, and soil type on MDD.

4. RESULTS AND ANALYSIS

4.1 Compaction Test Results

The Maximum Dry Density (MDD) results from the 27 experimental runs (Figure 3) reveal distinct soil-type-dependent compaction behavior, with polymer-modified silty sand (SM-P) achieving the

highest densities, followed by cement-modified silty sand (SM-C) and natural silty sand (SM-N), reflecting differences in bonding mechanisms and moisture sensitivity.

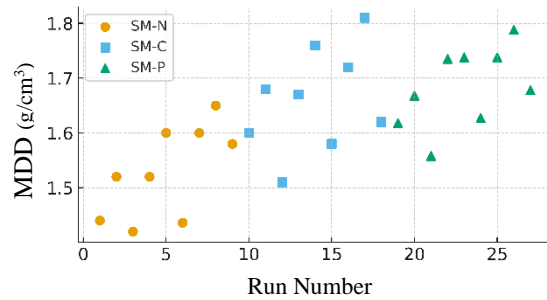


Fig. 3 Scatter plot of Maximum Dry Density (MDD) across 27 experimental runs grouped by soil type.

These trends are consistent with previous findings on polymer-treated and cement-stabilized soils and with reported compaction behavior of fine-grained and amended soils [3–5,15,17,20–23].

4.2 Effects of Compaction Parameters and Interactions

Experimental results indicate that Maximum Dry Density (MDD) is governed by both the main effects and interactions of soil type, compaction energy, and moisture condition (Figures 4 and 5). Polymer-modified silty sand (SM-P) consistently achieves the highest MDD, followed by cement-modified soil (SM-C) and natural silty sand (SM-N), reflecting differences in bonding mechanisms [14,17,20–22]. MDD increases monotonically with compaction energy from $0.5 \times$ to $1.5 \times$ Modified Proctor due to enhanced particle rearrangement, while peak density across all soils occurs at the Optimum Moisture Content (OMC). Both drier and wetter conditions reduce achievable density because of insufficient lubrication and excess pore-water pressure, respectively [6,11,14,15,17,19–22].

Interaction analysis further reveals pronounced soil-specific and nonlinear responses. As shown in Figures 5, SM-P exhibits the strongest response to increased compaction energy, whereas SM-C shows diminishing returns at high energy levels and greater sensitivity to moisture variation, achieving maximum MDD at $OMC+2\%$.

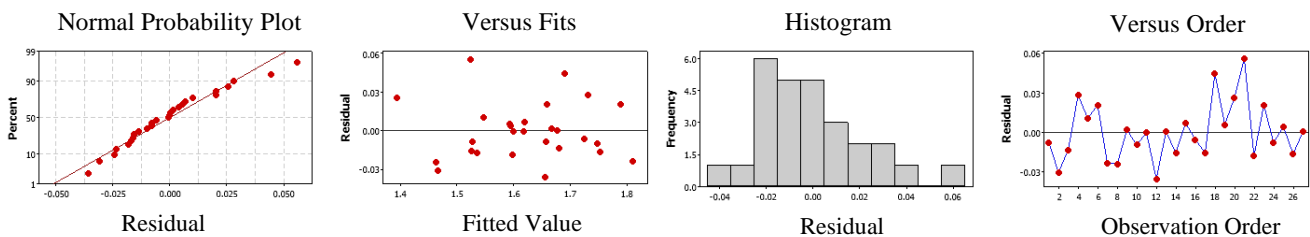


Fig. 2 Regression diagnostic plots for the developed MDD prediction model.

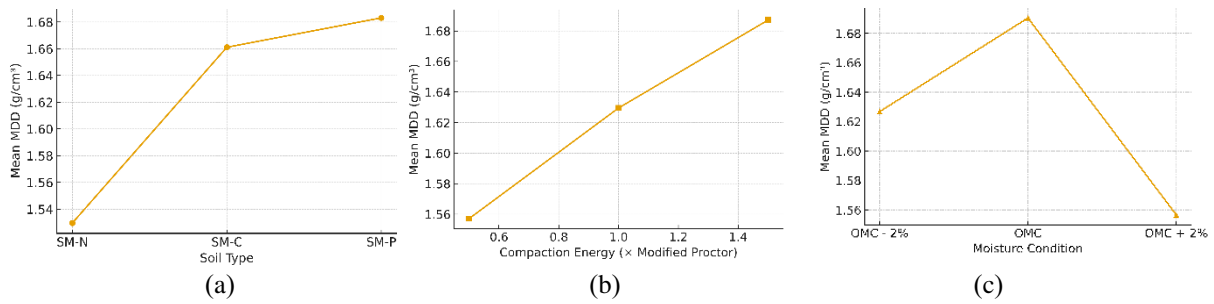


Fig. 4 Main effects of (a) soil type, (b) compaction energy, and (c) moisture condition on Maximum Dry Density (MDD)

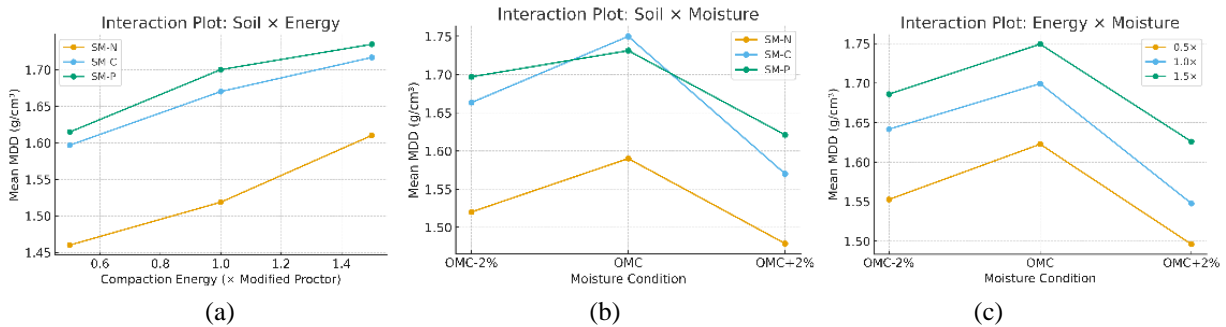


Fig. 5 Interpretation of Two-Factor Interaction Plots

In contrast, SM-P and SM-N perform optimally at OMC. Across all soils, the highest MDD consistently occurs at the combined condition of 1.5× compaction energy and OMC, and deviations from OMC cannot be compensated for by increased energy alone. These results emphasize the need for simultaneous control of soil type, moisture condition, and compaction energy to achieve reliable compaction performance.

4.3 Statistical Significance, Optimization and Sensitivity

Three-factor ANOVA confirms that soil type, compaction energy, and moisture condition, as well as their interactions, significantly affect Maximum Dry Density (MDD) ($p < 0.05$), indicating that silty sand compaction is governed by interdependent multi-variable mechanisms [6]. Based on the combined ANOVA and interaction analysis, optimal compaction conditions were identified. For all soils, 1.5× Modified Proctor energy yielded the highest MDD, while the optimum moisture condition depended on soil modification: SM-N and SM-P performed best at OMC, whereas SM-C achieved maximum density at OMC+2% due to moisture-enhanced hydration. These optimal conditions are summarized in Table 6 and provide soil-specific guidance for compaction optimization.

Table 6 summarizes the optimal compaction condition for each soil type

Soil Type	Optimal Energy	Optimal Moisture	Maximum MDD (g/cm ³)
SM-N	1.5×	OMC	1.81
SM-C	1.5×	OMC+2%	1.65
SM-P	1.5×	OMC	1.788

Effect-size analysis using eta-squared (η^2) further indicates that soil type is the dominant factor influencing MDD ($\eta^2 = 0.423$), followed by moisture condition ($\eta^2 = 0.275$) and compaction energy ($\eta^2 = 0.260$). Interaction effects contribute less than 4% of the total variance, indicating that MDD is primarily governed by main effects, while interactions refine the optimum compaction conditions. Overall, these findings emphasize the importance of soil-type-specific compaction strategies supported by statistical analysis to improve density performance and reduce variability in field applications.

5. DISCUSSION

The results confirm that the compaction behavior of silty sands in Pathum Thani is governed by soil modification, moisture condition, and compaction energy, as well as their interactions. Polymer-modified silty sand (SM-P) consistently achieved the highest Maximum Dry Density (MDD), demonstrating the effectiveness of polymer additives in enhancing densification, while cement-modified soil (SM-C) showed moderate improvement with greater sensitivity to moisture due to hydration-dependent bonding. These trends are consistent with previous studies on polymer-treated and cement-stabilized soils [3–6,15,17,18]. Moisture condition critically controls compaction efficiency. Across all soil types, MDD peaked near the Optimum Moisture Content (OMC), with density reductions observed under both drier and wetter conditions. Notably, SM-C achieved maximum MDD at OMC+2%, whereas SM-P and SM-N performed optimally at OMC, reflecting soil-specific moisture sensitivity [6,17,18,

22]. Compaction energy had a strong positive effect on MDD, with 1.5× Modified Proctor effort producing the highest densities. However, increased energy could not offset unfavorable moisture conditions, particularly under wet conditions where excess pore water limited densification. This behavior highlights the importance of simultaneous control of moisture and compaction effort [9,14,19,20]. Significant interaction effects further indicate that silty sand compaction is governed by nonlinear, multi-factor mechanisms. Polymer-modified soils benefit most from increased energy, while cement-modified soils are more moisture-sensitive, indicating that soil-type-specific compaction strategies are required to achieve reliable field performance. Overall, the proposed framework supports data-driven compaction optimization and provides practical guidance for earthwork planning and quality control in moisture-sensitive silty sand environments.

6. PRACTICAL IMPLICATIONS

This study provides data-driven guidance for compaction planning of natural and modified silty sands in Thailand. The proposed factorial–regression framework supports soil-type-specific compaction strategies for field application. Natural silty sand (SM-N) performs optimally at 1.5× Modified Proctor energy and OMC, cement-modified silty sand (SM-C) at OMC+2%, and polymer-modified silty sand (SM-P) at 1.5× energy and OMC, with strict moisture control required for SM-P to avoid density loss.

The regression model and compaction optimization matrix enable estimation of achievable dry density, prediction of moisture-induced density variation, and selection of appropriate compaction effort, thereby improving quality control, reducing trial-and-error, and enhancing construction efficiency and sustainability in silty sand earthworks.

7. CONCLUSION

This study investigated the effects of soil type, compaction energy, and moisture variation on the Maximum Dry Density (MDD) of natural and modified silty sands using a 3 × 3 × 3 full-factorial experimental design. The results confirm that all main factors and their interactions significantly influence compaction behavior. Polymer-modified silty sand (SM-P) achieved the highest MDD, while cement-modified soil (SM-C) exhibited moisture-sensitive behavior with optimal performance under slightly wetter conditions. Compaction energy showed a strong positive effect on MDD, with 1.5× Modified Proctor effort consistently producing the highest densities. Optimum Moisture Content (OMC) was critical for achieving peak MDD, while deviations of ±2% resulted in density reduction due to inadequate lubrication or excess pore-water pressure. The

developed second-order regression model demonstrated high predictive accuracy ($R^2 = 0.968$, $MAE = 0.015 \text{ g/cm}^3$, $RMSE = 0.0188 \text{ g/cm}^3$) and provides a reliable tool for estimating MDD under varying field conditions. Overall, the proposed compaction optimization framework enhances the reliability and efficiency of earthwork construction in silty sand deposits. Future research should focus on field validation, integration with advanced predictive techniques, and evaluation of additional soil stabilization methods under diverse environmental conditions.

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