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Research Article

Evaluating the role of nano-clay and nano-metakaolin in mitigating the collapsibility of gypseous soils

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Abstract

Gypseous soils present significant geotechnical challenges due to their highly variable and moisture-sensitive behavior. Although often considered mechanically stable in dry conditions, these soils are susceptible to sudden volumetric collapse upon wetting, leading to severe structural and infrastructural damage. This study evaluates the potential of nanomaterials specifically nano-clay and nano-metakaolin as stabilizing agents to mitigate the collapse susceptibility of gypseous soils. Representative soil samples, containing approximately 54% gypsum, were collected from Tikrit, Iraq, located about 200 km north of Baghdad. The experimental program involved preparing soil specimens treated with three nanomaterial contents (1%, 2%, and 3% by dry weight) and subjecting them to collapse potential and compressibility tests under both dry and soaked conditions. The results indicated that the inclusion of nanomaterials substantially decreased collapse potential and compressibility, with improvements becoming most significant at contents above 2%. At 3% incorporation, settlement was reduced by 40–60% before soaking and by 25–40% after soaking. These findings demonstrate that nanomaterials, particularly at higher dosages, enhance soil stability by reducing susceptibility to collapse and deformation. The study highlights the effectiveness of nanotechnology-based additives as a sustainable and innovative solution for stabilizing problematic gypseous soils in arid and semi-arid regions.

1. Introduction

Gypseous soils represent a subclass of collapsible soils that pose considerable geotechnical challenges owing to their unstable behavior under fluctuating moisture conditions. These soils are predominantly encountered in arid and semi-arid regions, where gypsum ($CaSO_4 \cdot 2H_2O$), a moderately soluble mineral, functions as a cementing agent between soil particles. While gypseous soils often exhibit acceptable strength in their dry state, their structural stability deteriorates rapidly upon wetting or saturation, resulting in sudden collapse or excessive settlement [1-3]. This collapse, commonly referred to as hydro collapse or hydro compaction, occurs primarily due to the dissolution of gypsum, which disrupts interparticle cementation and leads to particle rearrangement even in the absence of additional external loads. The underlying mechanism of collapse involves the dissolution of gypsum, which increases pore water content, reduces effective stress, and weakens interparticle bonding. Wetting accelerates this process, causing disintegration of the soil fabric, an increase in pore volume, and a consequent loss in shear strength and stiffness. Immersion in water further intensifies gypsum dissolution, along with other calcium-based minerals such as calcite, thereby reducing the soil's ability to sustain applied loads [4,5]. Several

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approaches have been developed to mitigate the collapse potential of gypseous soils. Conventional soil stabilization techniques typically involve the use of chemical additives such as lime, ordinary Portland cement, bitumen, and emulsified asphalt [6–8]. These stabilizing agents improve soil engineering properties primarily through physicochemical interactions, including cation exchange, flocculation–agglomeration, and pozzolanic reactions. The pozzolanic process leads to the formation of cementitious compounds such as calcium silicate hydrates (C–S–H) and calcium aluminate hydrates (C–A–H), which bind soil particles together and enhance interparticle bonding. As a result, treated soils exhibit increased shear strength and stiffness, reduced compressibility and plasticity, improved durability, lower permeability, and lower collapsibility [6–8]. These mechanisms collectively contribute to improved load-bearing capacity and long-term stability of problematic soils. However, while deep replacement and similar ground improvement methods can be effective, they are often economically unfeasible for large-scale applications. Consequently, increasing attention has been directed toward in-situ stabilization methods that improve soil performance without extensive excavation or replacement.

In this context, nanotechnology has emerged as a promising avenue in geotechnical engineering. Nanomaterials such as nano-clay and nano-metakaolin, owing to their ultrafine particle size and exceptionally high surface area, improve soil–particle interactions, refine pore structure, and accelerate the development of cementitious products [9,10]. Their ability to penetrate the soil microstructure enables pore filling and enhanced bonding between soil particles, leading to improved strength and durability. Although still an emerging field, several studies have demonstrated the effectiveness of nanomaterials in enhancing mechanical behavior, durability, and resistance to moisture-induced collapse in problematic soils [11,12]. Nanoparticles have been reported to reduce hydraulic conductivity, increase cohesion and internal friction, and mitigate collapse potential through their high reactivity and pozzolanic activity. A review of prior research on the stabilization of gypseous soils with nanomaterials highlights several consistent trends:

- The incorporation of nanomaterials reduced settlement by approximately 40–60%, depending on the dosage. This indicates a marked enhancement in the initial stiffness and structural of the soil.
- Even under saturated conditions, nanomaterial-treated soils exhibited a 25–40% reduction in settlement, confirming the durability and moisture resistance imparted by nanoparticle modification.
- The addition of nanomaterials significantly lowered soil compressibility, as reflected in decreased compression index (Cc) values and increased pre-consolidation pressure, thereby improving the load-bearing capacity.
- The most effective performance was consistently reported at 3% nanomaterial content, suggesting the existence of a threshold beyond which sufficient nanoparticle dispersion and reactivity achieve optimum stabilization.
- Both cohesion (c) and the angle of internal friction (ϕ) improved with nanomaterial treatment, particularly after curing, demonstrating the nanoparticles' role in strengthening interparticle bonding.
- Extended curing periods further enhanced soil strength, as continued reactions between nanoparticles and the soil matrix promoted additional bonding and pore structure refinement over time.

In the present study, gypseous soil samples containing 54% gypsum were collected from the Tikrit region to investigate the effect of nanomaterials on collapse potential and shear strength. Two types of nanomaterials nano-clay and nano-metakaolin were incorporated at varying dosages of 1%, 2%, and 3% by dry soil weight. Treated samples were subjected to curing and soaking to simulate field conditions and to evaluate their time-dependent performance. This study aims to systematically investigate the effectiveness of incorporating nanomaterials specifically nano-clay (NC) and nano-metakaolin (NM) into gypseous soils to achieve two primary geotechnical enhancements:

- Improvement of bearing capacity through microstructural modification, including pore filling, particle interlocking, and the formation of cementitious compounds; and

- Mitigation of foundation settlement by employing particle-scale stabilization mechanisms that reduce soil collapsibility and enhance resistance to moisture-induced volumetric changes.

2. Soil Sampling and Materials

2.1. Soil Sampling and Characterization

The gypseous soil employed in this study was obtained from a site located near Tikrit University, approximately 20 km southeast of Tikrit City and 220 km north of Baghdad, Iraq (34°40′51″N 43°39′17″E). The soil was excavated from depths ranging between 0.5 and 1.5 m below the natural ground surface, where field observations confirmed the presence of a gypsum-rich stratum. Laboratory analysis indicated that the sampled soil contained approximately 54% gypsum by weight, classifying it as highly collapsible. Upon collection, the soil was air-dried under controlled laboratory conditions for 48 hours to minimize moisture-induced changes and ensure consistency during testing. After oven-drying, the gypsum soil was manually crushed and homogenized using a mechanical mortar and pestle to break down agglomerated clumps and achieve a uniform, fine-grained texture. This manual crushing ensured consistent particle size distribution and minimized the presence of large aggregates that could bias experimental results. Similar procedures have been employed in previous soil stabilization studies to ensure uniformity in soil behavior across test samples. A comprehensive series of physical and chemical characterization tests was conducted in accordance with the procedures recommended by Head [13,14]. The tests included: Grain size distribution, Atterberg limits, Specific gravity, Natural water content, Gypsum content, and Soil classification. The grain size distribution curve of the untreated gypseous soil is shown in Figure 1, while the detailed results of the laboratory characterization are summarized in Table 1.

Table 1. Geotechnical and chemical properties of the investigated gypseous soil

Property	Value	Specification	Property	Value	Specification
Gs	2.54	ASTM D792-20	pH	8.01	
γ_{dmax}	17.6 kN/m³	ASTM D698	OMC	0.34%	
O. M.C.	11.8%	ASTM D4254	$CaCO_3$	4.6%	
D_{10}, D_{30}, D_{60} (mm)	0.13,0.21,0.41		Cl^-	0.057 mg/l	
Sand, S	94.4%		GC	54%	
Fines	5.6%	ASTM D-422	EC	2.43 µS/cm	ASTM D1125
Gravel	0%		ESP	13%	
Soil type (USCS)	SP		CEC	6.54 me/100g	ASTM D7503
TSS	78.5%	Earth manual E8	Ca	49.5%	
SO_3	26.75%	BS 1377: part 3	S	41.7%	
Fe	5.35%		Quartz, Gypsum, and Dolomite		XRD

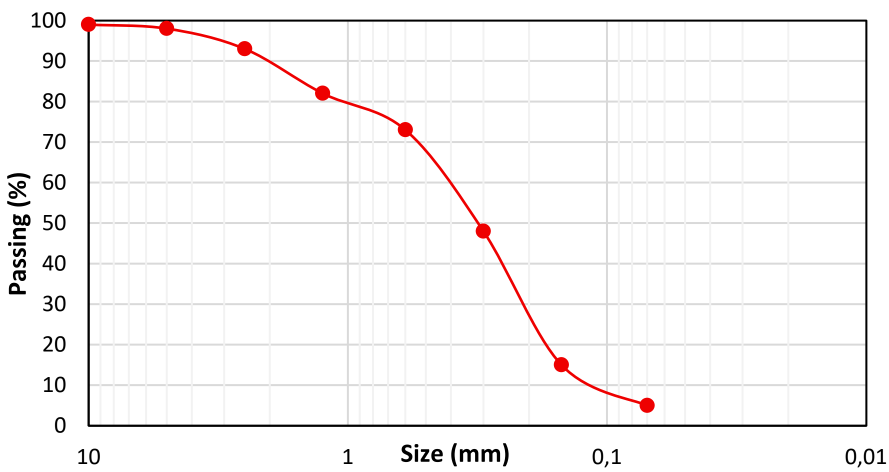

Fig. 1. Grain-size distribution curve of gypseous soil sample

2.2. Nanomaterials

Nano clay (NC) is synthesized primarily through mechanical exfoliation, a process that separates layered clay minerals into ultrafine particles with nanometric dimensions. The concentration of nano clay (NC) suspensions in water was adjusted based on soil texture, mineralogy, and engineering requirements, using mixing ratios of 1%, 2%, and 3% by dry weight of soil. A key parameter in preparing stable suspensions is the compound viscosity, which is strongly influenced by soil–solution interactions, particularly pH and salinity. From a practical perspective, NC is considered one of the most cost-effective nanomaterials and is extensively utilized in the production of high-performance nano-cementitious composites. Structurally, nano clay consists of silicate platelets with an approximate thickness of 1 nm and lateral dimensions in the range of 150–300 nm [15]. These morphological features, coupled with its chemical reactivity, enable NC to exhibit pozzolanic behavior at the nanoscale, thereby enhancing soil stabilization and accelerating strength development [11,16]. The particle size of NC in the gamma phase is typically within the range of 1–2 nm, underscoring its extremely fine-scale characteristics. A summary of the principal physical and chemical properties of NC is presented in Table 2.

Table 2. Physical properties and chemical composition of Nano clay

Properties	Value	Oxide composition	Content, %
Type of mineralization	Montmorillonite	Na_2O	0.98
Density (kN/m^3)	1.5 – 1.7	MgO	3.29
Diameter	1-2 nm	Al_2O_3	19.60
Special surface area	220-270	SiO_2	50.95
Conductivity of electrical	-25	K_2O	0.86
Coefficient of ion exchange	48	Cao	1.97
Empty gap	60 A	TiO_2	0.62
Color	Light yellow	Fe_2O_3	5.62
Moisture	1 –2%	LOI	15.45

Table 3. Physical properties and chemical composition of Nano-metakaolin

Properties	Value	Oxide composition	Content, %
Type of mineralization	Calcined kaolin	Na_2O	0.08
Density(kN/m^3)	0.5 – 0.7	MgO	0.151
Diameter	30 nm	Al_2O_3	45±2
Special surface area	100-150	SiO_2	53±2
Conductivity of electrical	-29	K_2O	0.071
Coefficient of ion exchange	48	Cao	0.193
Empty gap	60 A	TiO_2	0.78
Color	Off white	Fe_2O_3	0.268
Moisture	0.5%	LOI	13.56

Nano-metakaolin (NM) is a non-metallic mineral obtained through the controlled calcination of kaolinitic clay and claystone, consisting predominantly of minerals belonging to the kaolinite group. In its purified state, kaolin is characterized by its white color, smooth texture, and plasticity, making it a valuable industrial raw material. Metakaolin, and particularly its nanoscale derivative, exhibits high thermal stability and significant pozzolanic activity, which contribute to its widespread use in engineering and industrial applications. Owing to these properties, NM is extensively employed in the production of ceramics, refractory products, and specialty papers. Beyond these traditional applications, NM also plays a critical role in the manufacturing of paints, rubber composites, fillers, and enamel coatings, owing to its fine particle size, reactivity, and surface area. From a construction materials perspective, nanomaterials are widely recognized as supplementary cementitious materials (SCMs) that contribute to improved performance in blended binders. They accelerate pozzolanic reactions, refine pore structure, and enhance strength development, durability, and resistance to chemical degradation [17,18]. Notably, NM is also regarded as a key raw material in the production of high-quality white cement. The fundamental physical and chemical properties of nano-metakaolin, as reported in the literature, are summarized in Table 3 [19].

3. Physical Model and Testing

The experimental arrangement, illustrated in Figure 2, comprised a rigid soil container with internal dimensions of 600×600×400 mm, supported by a steel loading frame to ensure structural stability during testing. A square steel foundation plate measuring 100×100×20 mm was positioned at the center of the container to apply vertical loading. The loading process was executed using a mechanical hydraulic jack, securely mounted on the steel frame to deliver controlled and gradual load increments to the foundation model [20-22]. To simulate precipitation events, a movable rainfall simulation system was incorporated into the setup, enabling uniform wetting of the soil surface under controlled conditions. Vertical displacement of the foundation plate was continuously monitored using a Linear Variable Differential Transformer (LVDT), which was connected to a data acquisition system (Data Logger) to record real-time settlement data with high precision. Additional instrumentation and accessories integrated into the setup included:

- A 15-bar capacity load cell for accurate measurement of applied loads,
- An air compressor to operate pneumatic components where necessary,
- A nylon sheet to isolate the loading area during selected tests,
- A universal power supply system to maintain uninterrupted operation of equipment,
- A steel movable girder and fixed vertical loading frame to ensure stable alignment and uniform transmission of loads.

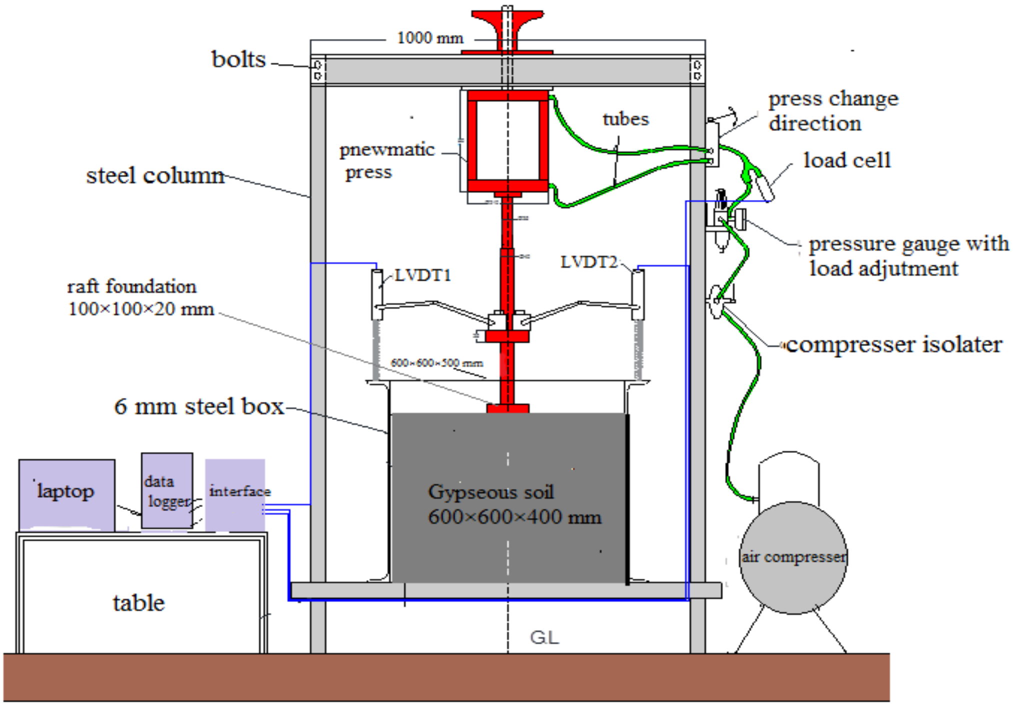

Fig. 2. Schematic diagram of physical model used in testing the soil samples

A controlled raining technique was employed to deposit the dry gypseous soil into the test container, ensuring the formation of a uniform soil layer with the desired density. For this purpose, a custom-designed raining system was developed. The effectiveness of this technique is governed primarily by two parameters: the drop height and the discharge rate, both of which directly influence the final density of the deposited soil layer [23]. To regulate the fall height, a movable roller mechanism was mounted at the top of the container, allowing precise adjustment of the soil drop distance. A series of four preliminary calibration trials were performed to determine the optimal fall height for achieving the target density. During these trials, the drop height was systematically varied while maintaining a constant fill volume. The in-situ density achieved in each trial was assessed by collecting soil samples in pre-weighed metal tins of known volume, placed at multiple locations within the container. The measured densities were then used to calculate the relative density (Dr), based on the maximum and minimum void ratios of the soil. The results were plotted as relative density versus drop height to establish the correlation. As shown in Figure 3, the target relative density of 40% was attained at a fall height of 725 mm. The fall height (725 mm) was therefore adopted in all subsequent tests to maintain uniform and consistent soil placement conditions.

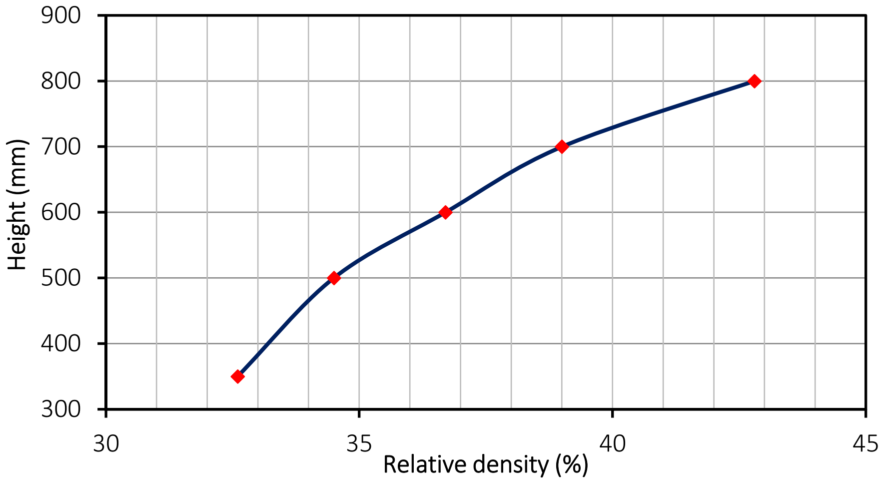

Fig. 3. Calibration curve of raining technique used in preparation of gypseous soil sample in the physical model

The mixing of nanomaterials with dry gypseous soil was carried out in two stages to ensure homogeneous soil samples. In the present study, the total volume of dry soil was first divided into several portions and placed in a square container measuring 500×500 mm. Each portion was evenly spread, and the required amount of nanomaterial was uniformly distributed over the soil surface using a fine sieve #200. In the second stage, all portions were combined and manually mixed for a minimum of 10 minutes to achieve uniform dispersion of the nanomaterials and ensure sample homogeneity. A comprehensive experimental study was carried out to investigate the effect of nanomaterials on the geotechnical behavior of gypseous soils under varying moisture conditions. In total, fourteen physical model tests were conducted, each subjected to incremental vertical loading while monitoring the corresponding settlement responses. The test matrix included the following groups:

- Six dry models of gypseous soil treated with 1%, 2%, and 3% additions of nano clay (NC) and nano metakaolin (NM).
- Six soaked models prepared with identical treatments, but tested under fully saturated conditions to evaluate the soil's hydro-mechanical response.
- Two untreated control models, one tested in the dry state and the other under saturated conditions, to provide baseline performance for comparison.

Saturation of the treated and untreated models was achieved by inducing upward seepage from the base of the soil container, thereby replicating realistic field scenarios such as groundwater table rise, seepage forces, or flooding events. This method ensured a controlled and uniform infiltration process, allowing a reliable assessment of soil collapse and settlement behavior. The adopted testing strategy provided a systematic framework for isolating the effects of nanomaterial type (NC vs. NM), treatment dosage (1–3%), and moisture condition (dry vs. saturated) on the settlement characteristics of gypseous soils.

4. Results and Discussion

4.1. Compressibility of Soil

Collapsible soils, while capable of supporting relatively high stresses under unsaturated conditions, undergo substantial volumetric strain when exposed to wetting, even without an increase in external loading. This behavior is primarily attributed to the dissolution of soluble salts, such as gypsum, and the subsequent breakdown of interparticle cementation bonds. To assess this phenomenon, seven gypseous soil specimens were examined: one untreated (natural) soil sample and six treated with nano clay (NC) and nano metakaolin (NM) at dosages of 1%, 2%, and 3% by dry weight, see Figures 4 and 5. The collapse potential (Cp) was determined using the single oedometer collapse test in accordance with ASTM D5333 (2003). The untreated soil exhibited a collapse potential of 10.2%, categorizing it as a highly collapsible soil. With the incorporation of nanomaterials, a marked reduction in collapse susceptibility was observed. At 3% NC, the collapse potential decreased to 2.66%, while 3% NM achieved an even lower value of 2.32%. These reductions represent a 74–77% improvement in collapse resistance, underscoring the efficacy of nanomaterials in stabilizing problematic gypsum-rich soils.

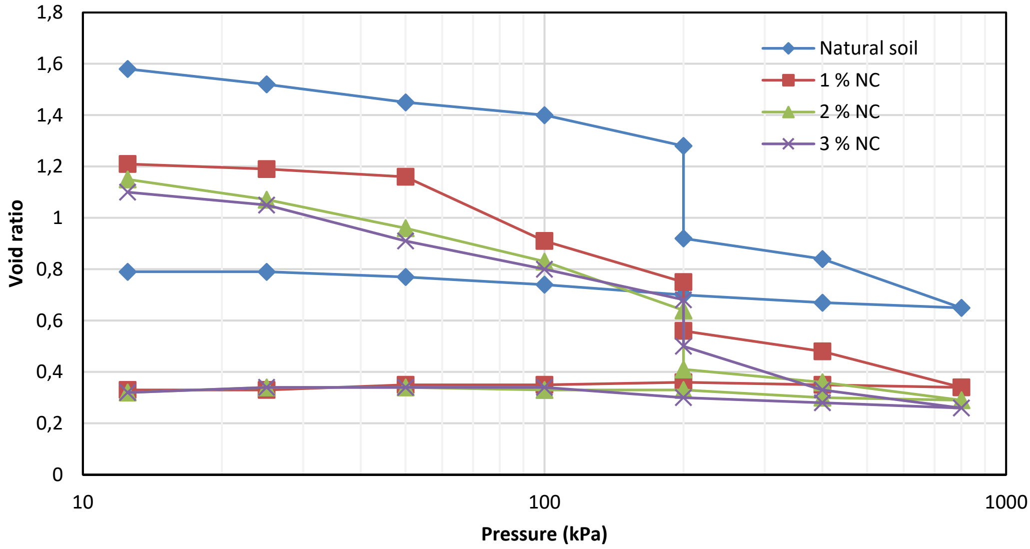

Fig. 4. Potential collapse tests of gypseous soil treated by Nano clay (NC)

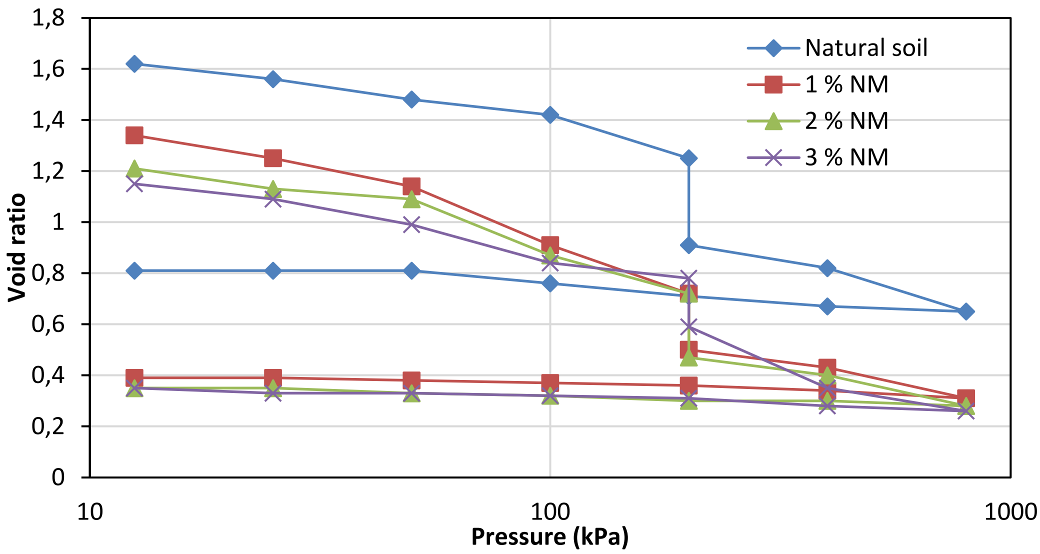

Fig. 5. Potential collapse tests of gypseous soil treated by Nano metakaolin (NM)

The observed improvements can be attributed to multiple mechanisms:

- Nanoparticles possess extremely high surface area-to-volume ratios, enabling them to occupy micropores and coat soil particles. This physical filling reduces the soil's porosity and restricts the pathways for water infiltration, thereby limiting wetting-induced volumetric strains. Additionally, the nanoparticles form bridges between soil grains, enhancing interparticle friction and cohesion at the micro-scale.

- In the case of NM, which is rich in reactive silica and alumina, pozzolanic reactions occur when the nanoparticles react with calcium ions from gypsum or lime content in the soil. This leads to the formation of secondary cementitious products, such as calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H), which chemically bond soil particles together. These new cementitious bonds reduce the solubility-driven collapse potential by creating a more chemically stable soil matrix.
- Nano clays possess negatively charged surfaces, which can attract cations (e.g., Ca^{2+}) in the soil solution, promoting particle flocculation and aggregation. This modifies the soil's fabric and increases effective stress between particles, resulting in higher resistance to sudden collapse upon wetting.
- The combination of physical pore filling, chemical bonding, and electrostatic particle aggregation increases the effective contact area between soil grains. This improves load distribution throughout the soil skeleton, reducing local stress concentrations and compressibility under applied loads or self-weight.
- By creating a dense, interconnected microstructure and chemically stabilizing reactive ions, nanomaterials slow down the dissolution rate of gypsum upon wetting. This mitigates one of the primary drivers of collapsibility, as the soil maintains its structural integrity even in the presence of water infiltration.

The comparative performance between NC and NM indicates that while both nanomaterials enhance collapse resistance, NM achieves superior stabilization due to the dual role of physical pore refinement and chemical pozzolanic activity. NC primarily acts through mechanical densification and surface charge interactions, whereas NM actively forms new cementitious phases that reinforce the soil skeleton. These mechanisms demonstrate that nanoscale interventions can address both the physical and chemical causes of collapse in gypseous soils. Furthermore, the results highlight the efficiency of using small nanomaterial dosages to induce significant soil improvement, making this approach more sustainable and cost-effective compared to conventional stabilizers such as lime or cement, which require larger quantities and longer curing times. This scientific understanding provides a pathway for targeted soil improvement strategies, particularly in environments prone to wetting-induced collapse, such as arid and semi-arid regions with gypsum-rich subsoils.

The superior performance of NM over NC is consistent with its higher pozzolanic activity and chemical reactivity, which enable more effective binding of soil particles. These findings align with previous research (e.g., Taha and Taha [11] Al-Murshedi et al. [24]), which reported that nanomaterial additives improve the geotechnical behavior of collapsible soils by reducing settlement and enhancing shear strength. Furthermore, the reduction in collapse potential to values below 3% suggests that treated soils transition from the category of highly collapsible to low or moderately collapsible, according to widely accepted classification criteria [25,26]. This transformation has significant practical implications: it enables the safe utilization of gypseous soils as foundation materials with minimal risk of sudden settlement upon wetting, thereby reducing the need for costly soil replacement or deep foundation systems. In conclusion, the experimental results clearly demonstrate that nanomaterials are effective stabilizers for gypseous soils, with nano metakaolin exhibiting superior performance compared to nano clay. The findings highlight the potential of nanotechnology as a sustainable and cost-efficient soil improvement strategy, particularly in arid and semi-arid regions where collapsible soils are widespread. The use of nano-metakaolin contributes to enhanced soil performance through micro-scale mechanisms such as pore filling, particle aggregation, and pozzolanic reactions, which collectively reduce soil collapsibility and improve strength characteristics. Compared with conventional stabilizers, nano-based additives require lower dosages to achieve comparable or superior performance, thereby reducing material consumption and associated environmental impacts. Moreover, the availability of metakaolin from locally sourced clay minerals enhances the economic feasibility of this approach for large-scale geotechnical applications in regions characterized by limited water resources and problematic soil conditions.

4.2. Load-Settlement

The findings suggest that nano-based stabilization could be a cost-effective and sustainable alternative to traditional stabilization methods such as cement or lime treatment, especially in arid and semi-arid regions where gypseous soils are widespread. Unlike bulk stabilizers, nanomaterials achieve significant improvements at relatively low dosages (≤3%), reducing both material consumption and environmental footprint. This aligns with global trends toward green and nano-enabled geotechnics. The stress–settlement relationships of the tested models were evaluated under both dry and soaked conditions, with ultimate deformations recorded after wetting (Figures 6 to 9). The untreated gypseous soil exhibited rapid acceleration of settlement upon flooding, reflecting the combined effects of gypsum dissolution, softening of the soil fabric, and loss of shear strength. In contrast, soils treated with nanomaterials displayed markedly reduced settlement rates and enhanced stability. Before soaking (dry condition), the soil response:

- NC-treated soils exhibited a 30–60% reduction in settlement, depending on dosage.
- NM-treated soils showed a 40–60% reduction, suggesting that the higher pozzolanic activity of nano metakaolin contributes to more effective soil stabilization.

While after soaking both nanomaterials continued to suppress deformation, with improvements attributed to cementitious reactions that progressed during and after wetting, leading to sustained strength and stiffness. Although the experimental results are promising, several challenges must be addressed before field-scale implementation:

- Durability under cyclic wetting–drying: Long-term exposure to fluctuating groundwater conditions may influence the persistence of the stabilization.
- Scalability and cost optimization: While nanoscale additives are effective, their cost and availability in large-scale projects must be evaluated against performance gains.
- Microstructural characterization: Advanced techniques (e.g., SEM, EDS, and micro-CT scanning) should be employed to quantify the distribution and bonding behavior of nanomaterials within the soil matrix.
- Coupled hydro-mechanical modeling: Incorporating nanomaterial effects into predictive models would allow better forecasting of settlement and collapse under field conditions.

The experimental findings demonstrate a clear improvement in the geotechnical behavior of gypseous soils treated with nanomaterials, with settlement reductions evident under both dry and soaked conditions. The observed mitigation is particularly significant given that untreated gypseous soils typically suffer from rapid and severe collapse upon saturation due to gypsum dissolution and the subsequent destabilization of the soil structure. While both additives improved soil performance, NM consistently outperformed NC across most loading stages.

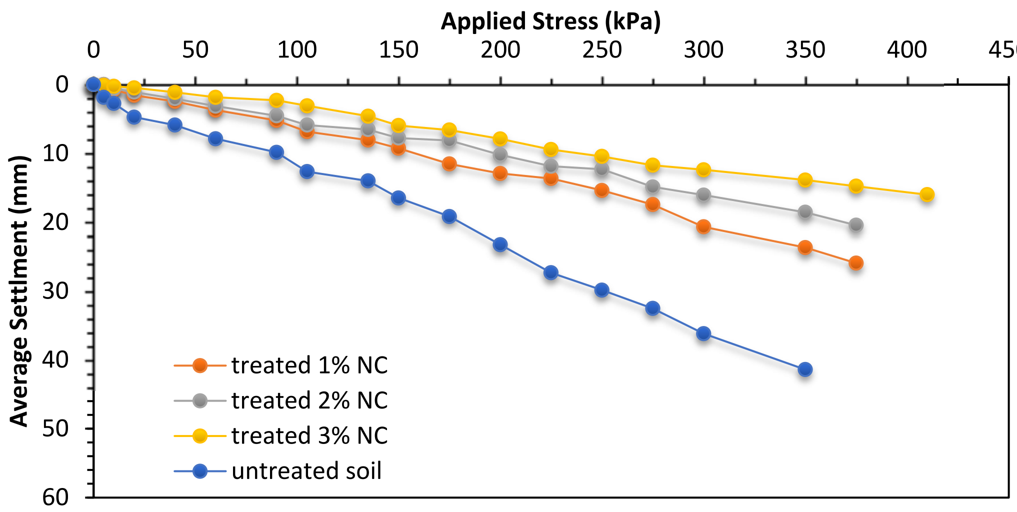

Fig. 6. Applied stress versus settlement of gypseous soil treated with NC in dry condition

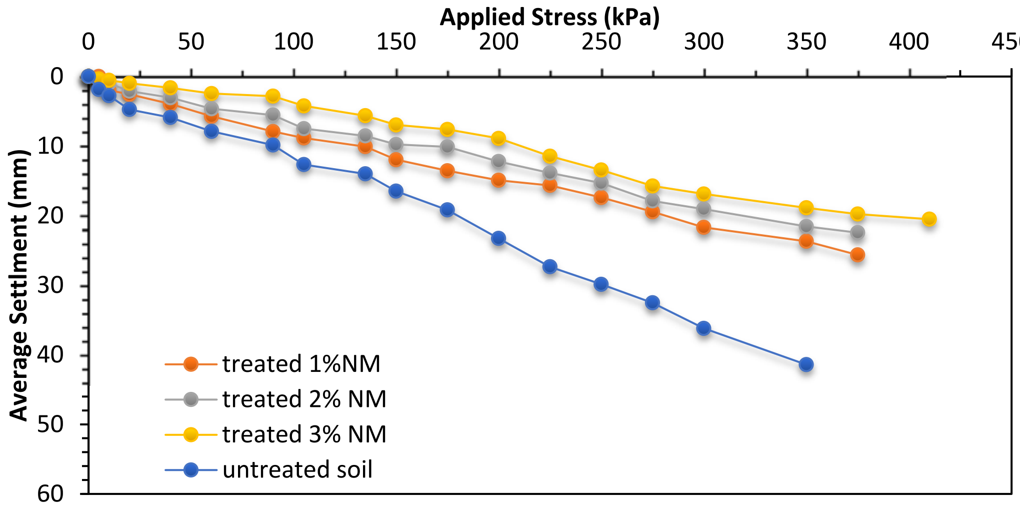

Fig. 7. Applied stress versus settlement of gypseous soil treated with NM in dry condition

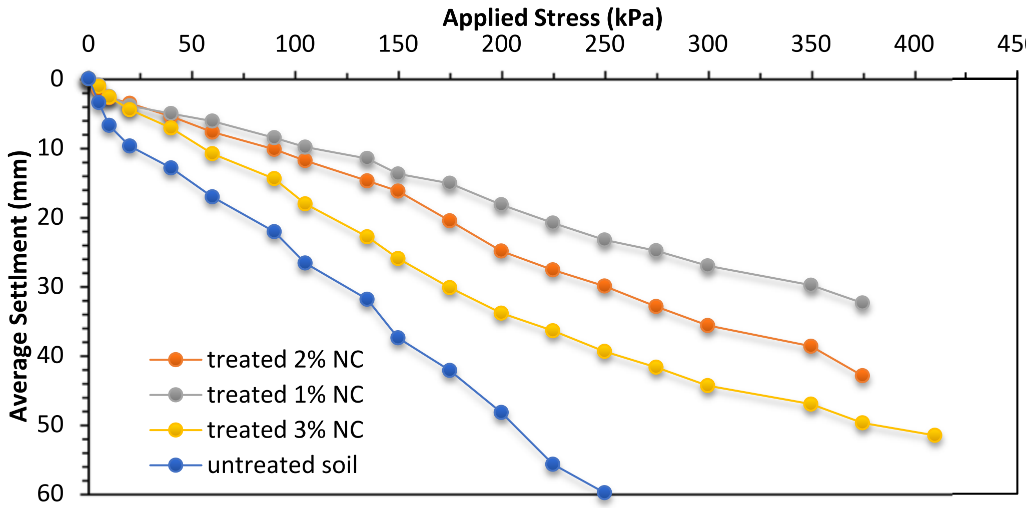

Fig. 8. Applied stress versus settlement of gypseous soil treated with NC after soaking

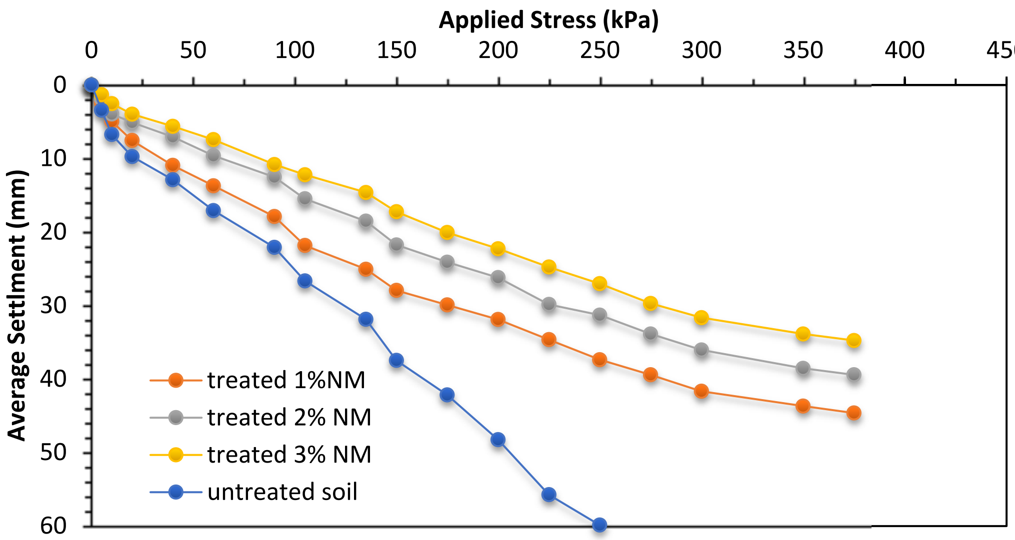

Fig. 9. Applied stress versus settlement of gypseous soil treated with NM after soaking

This can be attributed to the higher pozzolanic reactivity of NM, which accelerates the formation of stable cementitious products such as calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H). The finer particle size and higher surface reactivity of NM particles enable them to integrate more effectively into the soil matrix, leading to stronger particle interlocking and enhanced long-term stiffness. In contrast, NC primarily acts through physical mechanisms such as pore filling and particle bridging, which, while beneficial, do not yield the same chemical stabilization effects as NM.

The settlement reduction prior to soaking indicates that nanomaterials effectively densify and cement the soil structure even under dry conditions. Upon soaking, the untreated gypseous soils exhibited sharp settlement acceleration, consistent with literature reports of collapse strains exceeding 10% in soils with high gypsum content. However, the treated soils showed a much milder response, suggesting that nanomaterials not only densify the structure but also protect against gypsum dissolution pathways. This dual role underscores the importance of nanoscale additives in sustaining soil performance under fluctuating moisture conditions. The mechanisms of soil stabilization can be achieved by [7,27]:

- By clogging micro-pores, nanomaterials reduced the soil's permeability, thereby slowing water ingress and limiting the rate of gypsum dissolution.
- The pozzolanic activity of NM, and to a lesser extent NC, produced cementitious gels that bound soil particles together, compensating for strength losses induced by gypsum dissolution.
- The formation of continuous gel networks and reduced void ratios approved by SEM and XRD observations reported in similar studies which explain the observed improvements in compressibility and load-bearing capacity.

This study confirms that the incorporation of nano clay (NC) and nano metakaolin (NMK) significantly improves the geotechnical behavior of gypseous soils. The principal benefits include:

- A substantial reduction in collapse potential under both dry and soaked conditions,
- Noticeable decrease in compressibility and enhancement of shear strength,
- Improved durability and stability against moisture variations, which are critical in hydro-collapse-prone environments.

5. Conclusions

These findings demonstrate that nanotechnology-based stabilization represents a viable, cost-effective, and environmentally sustainable alternative to conventional stabilization methods, particularly in regions where traditional techniques are either ineffective or uneconomical. The primary objective of this research was to evaluate the effectiveness of nanomaterial additives in enhancing the bearing capacity and reducing the settlement of shallow foundations constructed on gypseous soils. The following key conclusions were drawn:

- The addition of nanomaterials provides a practical and innovative approach to mitigating excessive settlement. The improvement arises primarily from pore clogging, soil fabric refinement, and enhanced interparticle bonding induced by the nanoparticles. With increasing nanomaterial content, the collapsibility of compacted specimens decreased consistently.
- The compressibility of gypseous soil was markedly reduced by the addition of nanomaterials. However, the improvement trend indicates a threshold effect: beyond 2% content, additional nanomaterials provided diminishing benefits.
- Gypseous soils treated with 3% nanomaterials exhibited a 40–60% reduction in settlement before soaking, while under saturated conditions, the reduction ranged between 25–40%. This confirms the robustness of nanomaterials in enhancing soil performance under both dry and moisture-induced collapse scenarios, although the stabilization is more effective in unsaturated conditions.

Overall, the study highlights the potential of nanomaterials as soil stabilizers, with nano metakaolin showing slight significant performance compared to nano clay due to its higher pozzolanic reactivity and stronger contribution to cementitious bonding. It's recommended to study:

- It is recommended to conduct full-scale model tests or field investigations to obtain more reliable results and to better identify the practical challenges associated with the application of these techniques.
- Future studies should consider the use of different types of nanomaterials and varying dosage ratios to enhance the geotechnical behavior of various soil types.
- Further research is needed to evaluate the long-term durability, environmental impacts, and optimal dosage levels of nanoparticles used for soil improvement.

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