

Impact of bentonite content on electrical resistivity and compressive strength of cement paste for grounding system applications

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Received 15 September 2024

Revised 27 February 2025

Accepted 11 March 2025

Abstract

This study investigates the influence of bentonite content on the electrical resistivity and compressive strength of cement pastes for grounding system applications. Ordinary Portland Cement (OPC) and Non-Shrink Grout (NSG) were modified by addition of bentonite contents ranging from 0 to 50% by weight. Bulk and surface resistivity testing was conducted to evaluate the electrical properties. Compression testing was performed to determine mechanical performance. The experimental results indicated that the bulk electrical resistivity was significantly reduced due to the increased bentonite content. It decreased from 55.65 to 0.86 Ωm for OPC and from 325.55 to 0.69 Ωm for NSG after curing for 28 days. Although its electrical properties were improved, compressive strength was decreased from 18.52 to 0.06 MPa for OPC and from 18.91 to 0.07 MPa for NSG. Electrical resistivity and compressive strength exhibited strong correlations following exponential and power law relationships with moisture content, respectively. Finally, it was found that a 30% bentonite content offers an acceptable trade-off between electrical and mechanical properties for grounding applications in high-resistivity soils.

Keywords: Bentonite, Electrical resistivity, Compressive strength, Grounding system, Cement paste, Non-Shrink Grout

1. Introduction

An electrical installation cannot be complete without grounding systems. These are protective pathways to dissipate fault currents into the ground thereby avoiding equipment damage and personnel injury. Current standards [1] recommend achieving and maintaining ground resistance values of less than 5 Ω for system effectiveness. However, the recommended resistance in areas with high soil resistivity, rocky or sandy surfaces, cannot be easily achieved.

Researchers and engineers have developed ground enhancement materials (GEMs) that operate via two fundamentally different processes to overcome these shortcomings. The first category consists of hygroscopic materials (e.g., bentonite) which retain moisture and are used in mixtures to facilitate ionic conduction. The second category is comprised of conductive materials, carbon-based compounds that create direct electrical pathways regardless of moisture content. These materials are often introduced into cement-based matrices to preserve the stable contact of grounding electrodes and soil [2-5].

Extensive studies have been conducted on the development of electrically conductive cement-based materials. First, electrical resistivity as low as 5.3 Ωm was achieved with incorporation of carbon fiber and carbon black by Zhang et al. [3]. Then, a combination of carbon black, carbon nanotubes and steel fibers was used to enhance the conductivity by Ou et al. [4]. However, the general use of these conductive additives is infeasible due to their high material costs and complicated processing requirements [5].

Bentonite has received considerable attention among available GEMs due to its unique physicochemical properties. Its effectiveness has been studied in recent years by Hasan et al. [6], who showed that this is due to its ultrafine particle size distribution (4.75- μm mean particle diameter) relative to cement (75- μm mean particle diameter), high specific surface area, and cation exchange capacity. Furthermore, due to its inherent characteristics, natural abundance, and economic viability [7], bentonite is a particularly promising material for grounding applications.

Bentonite-based grounding systems were shown to maintain very low resistivity, ranging from 3000 to 2.4 Ωm , owing to their water retention capabilities, as discussed by Mohd Tadza et al. [8]. However, when mixed with cement, hardening may affect bentonite's water absorption capability and hence its long-term performance [9]. Complex interactions between bentonite and cement matrices demand a detailed investigation of the combined behaviors of such systems for grounding applications.

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doi: 10.14456/easr.2025.23

The present study systematically investigates the combined effects of bentonite content on both the electrical and mechanical properties using two distinct cementitious matrices, Ordinary Portland Cement (OPC) and Non-Shrink Grout (NSG). The selection of NSG along with OPC offers insights into the versatility of bentonite incorporation, as NSG gives better dimensional stability and precision in specialized applications [10]. This research aims to (i) quantify the relationship between mixed bentonite and cement paste electrical resistivity over a wide range of volume fractions, (ii) assess their corresponding mechanical strength effects to delineate engineering application limits, (iii) identify the bentonite content range that is optimal for grounding applications considering both electrical and mechanical requirements, and (iv) develop material property predictive models from composition parameters. This work will serve as a guideline for developing more efficient and cost-effective grounding systems for difficult soil conditions.

2. Materials and methods

2.1 Materials

Two types of cementitious materials were employed in this study, Ordinary Portland Cement (OPC) and Non-Shrink Grout (NSG). NSG is a cementitious material with special properties that alleviate shrinkage during setting and hardening. It is especially suited for use in applications where high dimensional stability and precision are required. Unlike the conventional OPC, NSG involves particular admixtures and fine particles to control volume change and to increase flowability without compromising high-strength development. The NSG used in this study is a commercial grout composed of Portland cement, silica fume, and shrinkage-reducing admixtures. Improved flowability and lower segregation potential are achieved with a fine particle distribution of 1–100 μm and a specific gravity of 2.98.

Due to the complex nature of cement-based materials considering the impacts of both the crystalline phases and total elemental composition on electrical conductivity [6], both X-ray diffraction (XRD) and X-ray fluorescence spectroscopy (XRF) analyses are necessary. XRD provides information about specific crystalline phases that could contribute to electrically conducting pathways. In contrast, XRF gives a full picture of a material's elemental composition, including amorphous phases, that could play a significant role in determining its electrical properties. XRF analysis of OPC and NSG demonstrated that these materials are composed of calcium-based compounds with CaO contents of 88.91±1.13% and 78.70±0.89%, respectively (see Table 1). With silica fume incorporated, NSG had a higher SiO₂ + Al₂O₃ content (15.02%) than OPC (8.15%). XRD analysis (Table 2 and Figure 1) indicated that OPC is composed mainly of SiO₂ (32.3%) and CaCO₃ (48.5%), while NSG primarily contains SiO₂ (40.1%) and Fe₂O₃ (21.6%).

This study used commercial bentonite with an 800 m²/g specific surface area. Major constituents estimated by XRF analysis were SiO₂+Al₂O₃ (57.88±2.67%), Fe₂O₃ (23.26±1.55%) and CaO (11.05±0.67%). XRD analysis indicated that the crystalline composition consisted of Al₂O₃ (13.4%), SiO₂ (9.3%), and CaCO₃ (11.5%) as major phases and TiO₂ and Fe₂O₃ as minor phases. The crystalline nature of these phases was confirmed from their diffraction patterns (Figure 1), presenting characteristic peaks of the identified compounds.

Table 1 Chemical composition of materials from X-ray fluorescence spectroscopy (XRF)

Oxides (wt.%)	Bentonite	OPC	NSG
SiO ₂ +Al ₂ O ₃	57.88±2.67	8.15±1.18	15.02±1.11
CaO	11.05±0.67	88.91±1.13	78.70±0.89
Fe ₂ O ₃	23.26±1.55	1.13±0.02	3.59±0.06
TiO ₂	4.70±0.30	0.08±0.00	0.16±0.01
P ₂ O ₅	2.47±0.25	0.87±0.09	1.28±0.22
SO ₃	0.59±0.06	0.78±0.08	1.15±0.12
ZnO	0.02±0.00	0.01±0.00	0.03±0.00
K ₂ O	0.02±0.00	0.05±0.01	0.09±0.01
Loss on ignition	0.01±0.00	0.02±0.00	0.02±0.00
Total	100.00	100.00	100.04

Note: Values represent means ± standard deviations from five measurements

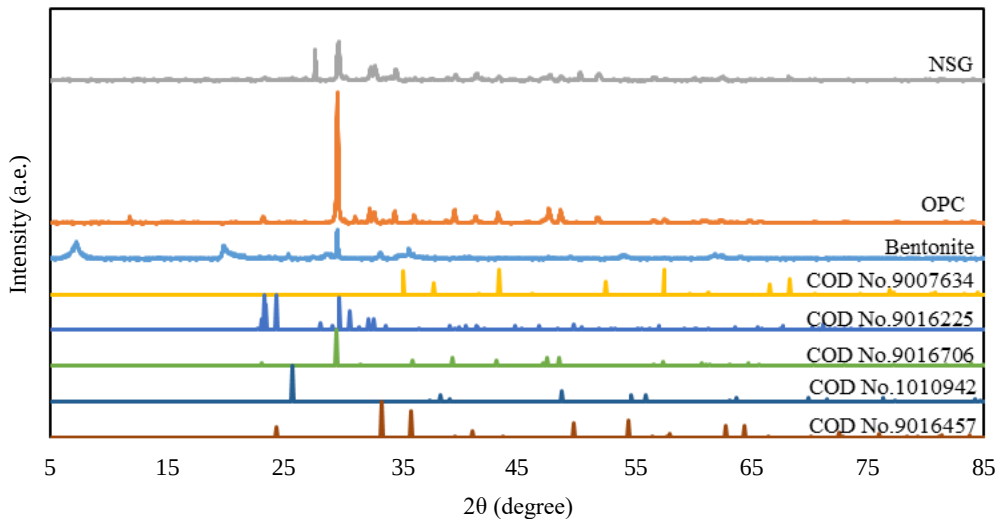


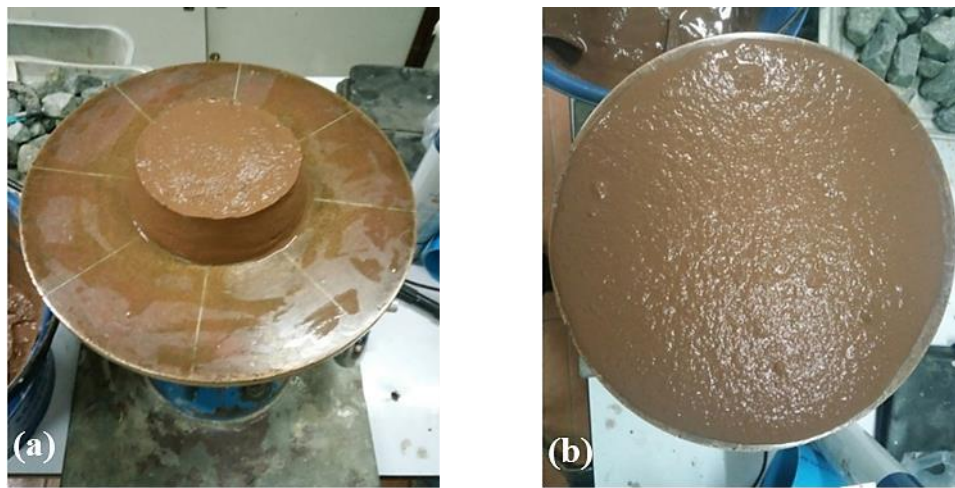
Figure 1 X-ray diffraction patterns of bentonite, OPC, and NSG

Table 2 Crystalline phase composition of materials from X-ray diffraction (XRD)

Phase	Weight percentage (%)		
	Bentonite	OPC	NSG
Al ₂ O ₃	15.90	16.60	13.40
SiO ₂	40.10	32.30	69.30
CaCO ₃	9.90	48.50	11.50
TiO ₂	12.50	1.00	3.30
Fe ₂ O ₃	21.60	1.60	2.50
Total	100.0	100.00	100.00

2.2 Mix proportions

Six mix proportions were prepared for each cementitious material (OPC and NSG) with bentonite contents ranging from 0 to 50% by weight of the binder. The water-to-binder ratio (WBR) was determined through flow table testing according to the ASTM C230/C230M standard specification for flow testing of hydraulic cement mortars [11]. The flow table test procedure is depicted in Figure 2. As shown in Table 3, the WBR increased substantially with the bentonite content, ranging from 0.45 at 0% bentonite to 3.60 at 50% bentonite. The flow values also showed a consistent increase with bentonite content, ranging from 105.21±5.07% to 150.45±3.68% for OPC mixtures and 105.22±4.97% to 153.70±1.53% for NSG mixtures. These significant increases in WBR and flow values are attributed to bentonite's high specific surface area and water adsorption capacity. Three replicates of each sample were prepared and tested to ensure reproducibility of the results.

**Figure 2** WBR measurements using a flow table test (a) initial stage of the test, and (b) final stage of the test**Table 3** Mix proportions and water requirements of cement-bentonite mixtures

Mix Type	Cement* (%)	Bentonite (%)	Water-to-Binder (WBR)		Flow value Average±SD (%)
			Range	Average±SD	
OPC	100	0	0.40 - 0.50	0.45±0.05	105.21±5.07
	90	10	0.50 - 0.70	0.60±0.10	116.95±7.67
	80	20	0.80 - 1.00	0.90±0.10	129.43±5.61
	70	30	1.40 - 1.80	1.60±0.20	138.44±7.24
	60	40	2.20 - 2.60	2.40±0.20	143.79±7.62
	50	50	3.40 - 3.80	3.60±0.20	150.45±3.68
NSG	100	0	0.40 - 0.50	0.45±0.05	105.22±4.97
	90	10	0.50 - 0.70	0.60±0.10	120.35±5.16
	80	20	0.80 - 1.00	0.90±0.10	139.61±7.15
	70	30	1.40 - 1.80	1.60±0.20	148.56±5.50
	60	40	2.20 - 2.60	2.40±0.20	151.62±2.97
	50	50	3.40 - 3.80	3.60±0.20	153.70±1.53

*Cement refers to either OPC or NSG.

Note: Values represent means ± standard deviations of three measurements.

2.3 Sample preparation and curing

Cylindrical specimens were prepared using 84-mm diameter PVC molds, as shown in Figure 3. The specimen heights varied from 163 to 178 mm due to different water requirements and compaction characteristics of varying bentonite contents. This is attributed to bentonite's high water absorption and swelling capacity. Preparation began with blending cement/grout and bentonite in a rotary mixer for 5 minutes to ensure uniform distribution in the cementitious matrix. Distilled water was then gradually added while stirring, followed by 5 minutes of additional mixing to achieve a smooth paste. The fresh mixture was cast in three layers, each compacted on a vibrating table for 30 seconds to remove voids and achieve uniform density.



Figure 3 Sample casting

The curing protocol was developed based on practical considerations and established research findings [12]. Specimens were carefully demolded after initially setting for 24 hours at room temperature ($23 \pm 2^\circ\text{C}$) under plastic sheets, as shown in Figure 4. This was done to reduce moisture evaporation. The subsequent curing regime consisted of two stages, considering that electrical resistivity rapidly changes during early aging. Initially, specimens underwent air drying at room temperature ($23 \pm 2^\circ\text{C}$) and controlled relative humidity ($50 \pm 5\%$) for three days, allowing for controlled early-age moisture loss while simulating real field conditions. Subsequently, specimens were subjected to moist curing under plastic sheeting for 15 days, with relative humidity maintained above 90%. The conditions were monitored using digital hygrometers.



Figure 4 Sample curing

2.4 Testing methods

2.4.1 Electrical resistivity measurements

Electrical resistivity measurements were made using a Proceq Model Resipod electrical resistivity meter (Proceq SA, Switzerland). The electrical properties were measured after 28 days of curing to compare the results at a standard concrete age. Two methods were employed to ensure comprehensive characterization.

The first technique was determination of bulk resistivity following ASTM C1876 [13], as shown in Figure 5(a). The samples were sandwiched between two water-soaked foam pads to ensure a good electrical connection. Resistance was recorded, and the bulk resistivity (ρ) was calculated as:

$$\rho = K * R_{cylinder} \quad (1)$$

where K is a geometric factor depending on specimen dimensions ($K = A/L$, where A is cross-sectional area and L is length), and $R_{cylinder}$ is the corrected resistance calculated from

$$R_{cylinder} = R_{measured} - R_{upper} - R_{lower} \quad (2)$$

where $R_{measured}$ is the resistance reading with specimen and foam pads. R_{upper} and R_{lower} are the foam pad resistances.

In the second method, surface resistivity was determined according to AASHTO TP 95 [14]. Figure 5(b) shows that this resistivity was measured directly on the sample surfaces using a four-probe method. Two electrodes provided current and the remaining two were used for measurements. They were equally spaced on the sample surfaces. For each sample, four measurements were taken at separate locations on the circumference of the cylinder. Average values were determined.

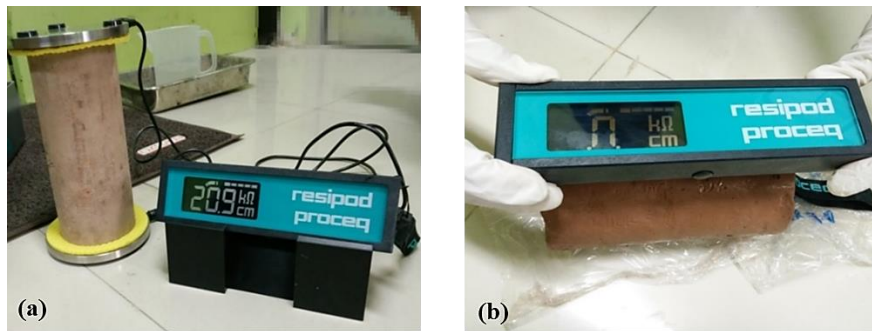


Figure 5 (a) Bulk resistivity, and (b) surface resistivity measurements

2.4.2 Compressive strength testing

Two different loading protocols optimized for separate material compositions were applied to evaluate mechanical properties. Compression tests were performed on specimens with 0-20% bentonite using a compression testing machine (ADR 3000, ELE International, United Kingdom), as shown in Figure 6(a), at a loading rate of 0.25 MPa/s according to ASTM C39/C39M [15]. This approach applies to conventional cement-based materials with rapid strength development. Specimens with 30 to 50% bentonite were tested using an unconfined compression test, as presented in Figure 6(b). These tests were done under strain control at 1%/min following ASTM D2166/D2166M [16]. This was done to account for their more pronounced clay-like behavior and greater deformation capacity while still assuring controlled failure modes.

Preliminary testing established the equivalence of these two loading rates. At a 170-mm specimen height, a 1%/min strain rate is roughly equivalent to a 1.7 mm/min deformation rate. Stress development rates were comparable to the 0.25 MPa/s stress development rate specified in ASTM C39/C39M [15]. This was done to ensure uniform strength evaluation among all mixture compositions when applied to specimens with 20% bentonite content.

Dual testing methodology enables a comprehensive understanding of the mechanical and electrical property relationships of all mixture compositions. At lower bentonite concentrations (0-20%), electrical conductivity is governed by pore solution characteristics. For higher concentrations (30-50%), both electrical conductivity and mechanical response are governed by clay-like behavior [5]. The testing approach thus gives insight into the transition between these two behavioral regimes and the implications for practical grounding applications. Three mix designs for each formulation were used in specimen testing. Average values are reported.

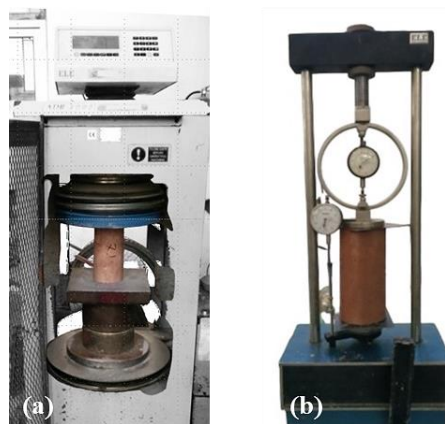


Figure 6 Compressive strength tests (a) strength determination using a compression testing machine, and (b) unconfined compression testing

2.4.3 Moisture content determination

Sample moisture contents were determined according to ASTM D4959 [17]. The cylinders were tested for resistivity and strength. After sample failure, the inner cores were taken. These samples were then weighed, placed in an oven at 105 °C for 24 hours, and reweighed once again. Moisture content is presented as the percentage of the sample oven dried weight.

3. Results

3.1 Electrical resistivity

After curing for 28 days, the electrical resistivity of cement paste samples with varying amounts of bentonite was determined. Figure 7 shows that bulk and surface resistivity decreased as bentonite content was increased for both OPC and NSG samples. The trend is consistent with previous work on conductive cementitious materials [3, 9].

The bulk and surface resistivity of OPC samples decreased from 55.65 and 102.67 Ωm (control mix) to 0.86 and 0.90 Ωm (50% bentonite), respectively. The NSG samples showed more initial reduction in the bulk resistivity, from 325.55 to 0.69 Ωm , and surface resistivity, from 356.67 to 0.90 Ωm . These reductions are significant and consistent with previous studies of bentonite-modified materials [18].

This agrees with earlier research [12], where the surface resistivity values were generally 5–10% higher than bulk measurements. XRF analysis confirmed that the more substantial resistivity reduction in NSG samples was achieved because of a higher $\text{SiO}_2 + \text{Al}_2\text{O}_3$ (15.02%) content than OPC (8.15%).

Due to the high water demand for bentonite, workability must be maintained across different bentonite contents, which requires varying the water-to-binder ratios (WBRs). The electrical properties of the samples are directly related to the WBR and the bentonite content. This is due to the consistent decrease in resistivity with increased bentonite content, even though the WBR is higher.

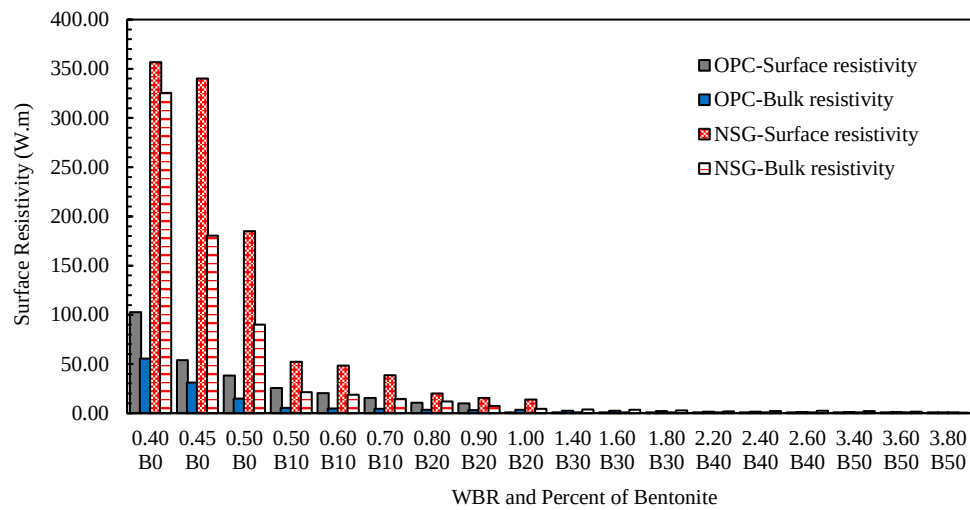


Figure 7 Effects of bentonite content on the electrical resistivity of OPC and NSG samples

3.2 Compressive strength

In Figure 8, incorporation of bentonite considerably affected the compressive strength of the samples, showing trends similar to soil-cement resistivity correlations described by Vincent et al. [19]. The 28-day compressive strength for OPC specimens decreased from 18.52 (control mix) to 0.06 MPa (50% bentonite). The same bentonite content range reduced strength from 18.91 to 0.07 MPa for NSG samples. This strength reduction pattern is in agreement with recent studies on bentonite-modified cementitious materials [6, 20].

The relationship between bentonite content and compressive strength demonstrates two distinct phases. These are a steep drop-off between a 0–20% bentonite content and a more gradual reduction. The complex interaction between bentonite and cement particles, as well as the greater water demand with higher bentonite contents [5] can explain this behavior.

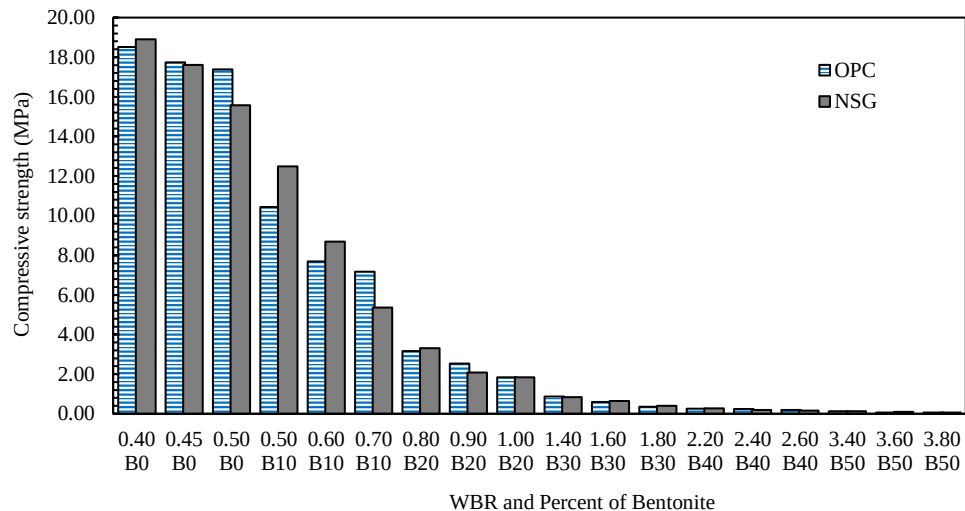


Figure 8 Effects of bentonite content on compressive strength of OPC and NSG samples

3.3 Moisture content

In Figure 9, the moisture content fluctuates greatly with bentonite content. Moisture content for OPC samples varied from 19.08 to 322.81%, and NSG samples ranged from 5.25 to 319.07%. Bentonite's exceptional water retention capacity, due to its layered silicate structure and high specific surface area (800 m²/g) [9], is characterized by notably high moisture contents (>100%).

The high moisture retention of bentonite reported here can be attributed to its ability to retain water within its interlayer spaces and through surface adsorption [18, 19]. The relationship between moisture content and electrical resistivity is well established. Resistivity decreases at greater moisture contents [12, 20].

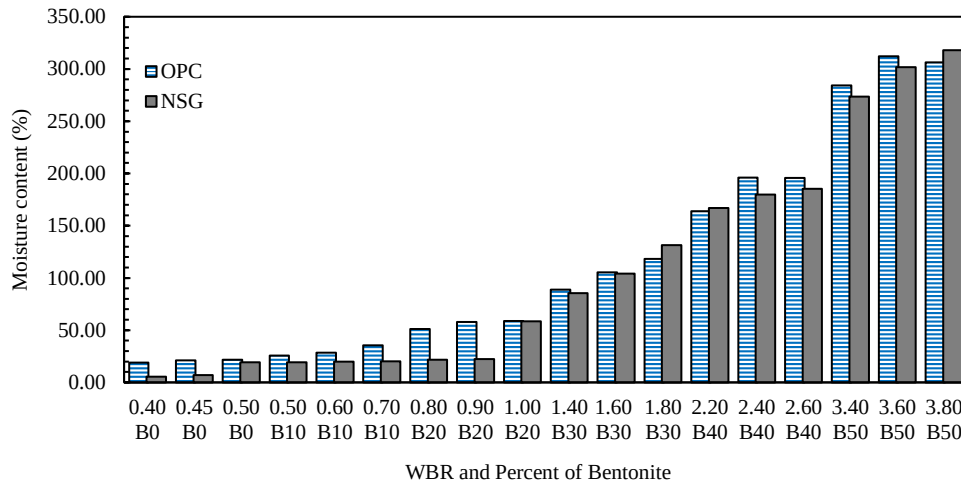


Figure 9 Variation in moisture content with different bentonite percentages for OPC and NSG samples

3.4 Compressive strength and electrical resistivity

The relationships between electrical resistivity (bulk and surface) and compressive strength for OPC and NSG samples are presented in Figure 10. They are consistent with Vincent's observations on cementitious materials [19]. Both cement types showed very strong logarithmic correlations. Equations (3) and (4) present the relationships between bulk resistivity (ρ_b) of cementitious materials and their compressive strengths. Equations (5) and (6) show the relationships between the surface resistivity (ρ_s) of the cementitious material and compressive strength (σ).

$$\text{OPC, } \rho_b = 1.5622e^{0.1616\sigma} (R^2 = 0.90) \quad (3)$$

$$\text{NSG, } \rho_b = 2.2968e^{0.2465\sigma} (R^2 = 0.91) \quad (4)$$

$$\text{OPC, } \rho_s = 1.5132e^{0.3203\sigma} (R^2 = 0.84) \quad (5)$$

$$\text{NSG, } \rho_s = 1.1801e^{0.2454\sigma} (R^2 = 0.84) \quad (6)$$

where σ is the compressive strength (MPa), ρ_b is the bulk resistivity (Ωm), and ρ_s is the surface resistivity (Ωm).

Strong correlations between electrical resistivity and compressive strength suggest that microstructural features, such as the pore structure and degree of hydration, govern the two properties. These relationships are exponential. Small changes in strength can significantly alter resistivity, especially at higher strengths. At all bentonite contents, surface resistivity measurements were consistently higher (5–10%) than bulk resistivity measurements. Reports of similar logarithmic correlations [3, 10, 20] in earlier studies concerning conductive cementitious materials are consistent with these results.

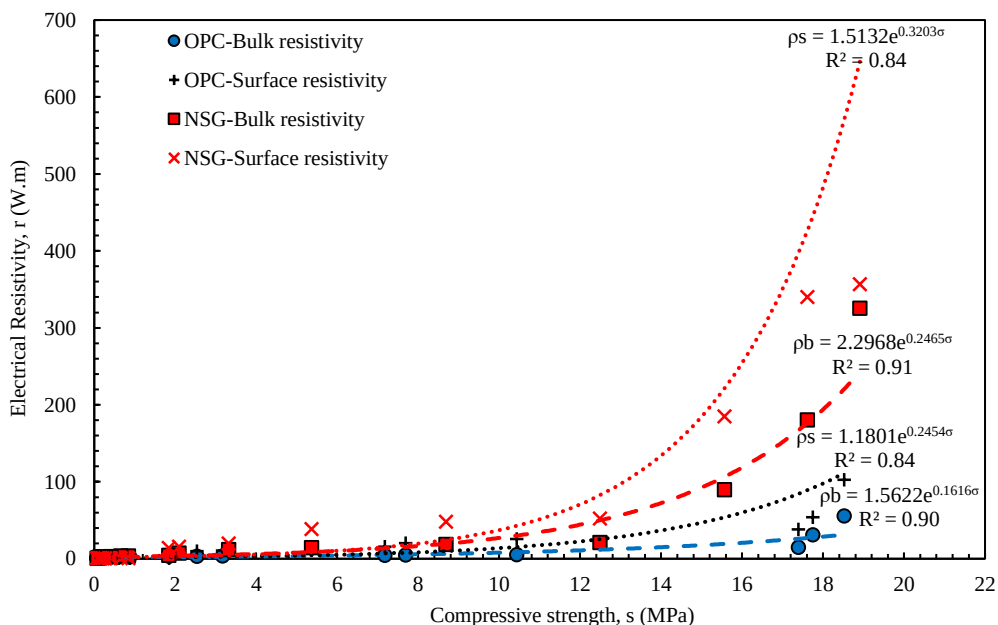


Figure 10 Correlations between electrical resistivity and compressive strength

3.5 Moisture content and electrical resistivity

Figure 11 demonstrates that the relationship between moisture content (w) and electrical resistivity can be expressed by power law functions for both OPC and NSG samples. Equations (7) and (8) are correlations between the bulk resistivity (ρ_b) of OPC and NSG samples and moisture content. Finally, Equations (9) and (10) correlate the surface resistivity (ρ_s) of OPC and NSG samples with moisture content.

$$\text{OPC, } \rho_b = 306.95w^{-1.034} (R^2 = 0.80) \quad (7)$$

$$\text{NSG; } \rho_b = 1065.5w^{-1.224} (R^2 = 0.88) \quad (8)$$

$$\text{OPC, } \rho_s = 4815.6w^{-1.638} (R^2 = 0.81) \quad (9)$$

$$\text{NSG, } \rho_s = 163.08w^{-0.537} (R^2 = 0.90) \quad (10)$$

Electrical properties are strongly influenced by moisture content. As confirmed by XRF analysis, differences in pore structure, water retention characteristics, and chemical composition appear responsible for the observed behavior.

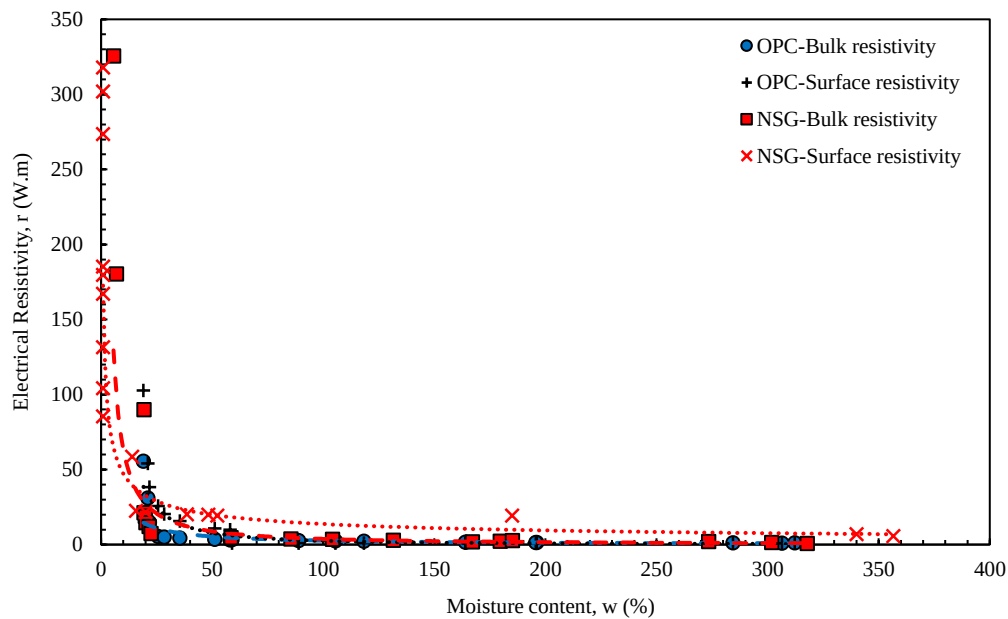


Figure 11 Correlations between electrical resistivity and moisture content

4. Discussion

4.1 Chemical composition and microstructure

A key finding from the XRF analysis was that OPC and NSG had significantly different $\text{SiO}_2 + \text{Al}_2\text{O}_3$ contents (8.15 and 15.02%, respectively). The higher $\text{SiO}_2 + \text{Al}_2\text{O}_3$ content of NSG, resulting chiefly from silica fume incorporation, affects its electrical and mechanical properties.

XRD patterns in both cases confirmed the crystalline character of the materials, and OPC was predominantly SiO_2 (32.3%) combined with CaCO_3 (48.5%). NSG contained more SiO_2 (40.1%) accompanied by Fe_2O_3 (21.6%). The bentonite-modified specimens demonstrate distinct electrical resistivity and strength development behavior due to these compositional differences [6].

4.2 Influence on electrical properties

Various mechanisms can be identified for the reduced electrical resistivity with greater bentonite contents. The high specific surface area (800 m^2/g) and cation exchange capacity of bentonite provide continuous ionic conduction pathways through the cement matrix [9], as discussed in recent reviews [6]. Furthermore, bentonite has a layered silicate structure that supports high water retention [6]. Moisture contents may exceed 300% at high bentonite contents.

The greater reduction in initial resistivity of NSG samples correlates with their higher $\text{SiO}_2 + \text{Al}_2\text{O}_3$ contents, indicating that a silica-rich composition favors ionic conduction mechanisms. An effective means of modifying the electrical properties of both cements is found in the systematic decrease of the resistivity with increasing bentonite content.

4.3 Influence on mechanical properties

The selection of NSG in conjunction with OPC was driven by a strategic need to overcome the practical limitations of OPC in field applications. These problems included shrinkage issues that undermine the long-term stability of grounding systems. Androvitsaneas et al. [2] indicated that material shrinkage can have a significant effect on grounding system performance. This is because material

shrinkage can result in air gaps forming between the grounding electrode and surrounding soil. NSG use offers better dimensional stability during setting and hardening than conventional OPC. Therefore, better electrode-soil contact is maintained.

Changes in both material composition and microstructure result in a progressive decrease of compressive strength with increasing bentonite content [3, 6, 7]. This is mainly due to the higher water demand of bentonite systems, which require water to binder ratios of 3.8 for a 50% bentonite content [6] to develop a cement matrix. However, this requirement for water enhances bentonite's electrical conductivity while imparting a more porous microstructure that affects mechanical strength development.

4.4 Mathematical relationships and property correlations

The relationship between electrical resistivity, compressive strength, and moisture content demonstrates the complex interactions within bentonite-modified cement pastes. Compressive strength exponentially correlates with electrical resistivity for OPC and NSG samples. The exponential coefficients of NSG samples were higher than those of OPC, which suggests that the NSG electrical properties are more sensitive to structural changes.

Power law relationships between moisture content and electrical resistivity demonstrate the critical role of water in electrical conductivity. The divergence of exponents between the OPC and NSG samples reveals the different sensitivities to moisture changes due to their varied microstructural characteristics and composition.

Resistivity measurement results show a plateau effect. A bentonite content greater than 30% does not show remarkably reduced electrical resistivity. This behavior indicates saturation in conductive pathway formation, which can be explained by two mechanisms. First, the limit on the maximum capacity for continuous ionic pathways is reached. Second, the high water content (>300%) present at these bentonite levels may provide a stability threshold in the electrical properties.

4.5 Implications for practical applications

Experimental results indicate that both OPC and NSG can be effectively used as a base material for bentonite-modified grounding systems. However, they have different properties. NSG is specially formulated, resulting in superior dimensional stability and more consistent performance characteristics. However, it is expensive, so careful consideration is required in real-life applications.

Many interrelated factors [6] may be considered when selecting a material for grounding applications. Initial and sustained electrical performance are important for the system, while physical stability and resistivity to shrinkage are significant in achieving consistent electrode-soil contact [2]. However, this correlation is very strong indicating that the moisture level plays a critical role under field conditions. Technical considerations must be balanced against economic factors where the initial material costs, as well as long-term maintenance requirements, are part of the budget under consideration.

4.6 Future research directions

The fundamental relationships found between the material composition, electrical, and mechanical characteristics of bentonite-modified cement pastes serve as a foundation for future research in three key areas [6]. Although the theory is developed, the most pressing issue is the understanding that mixtures must be field tested over a wide range of soil conditions, especially where soil resistivity is low. Prior to field implementation, comprehensive soil resistivity testing is essential. Recent successful approaches by Arjweh et al. [21] demonstrate effective methods using 2D electrical resistivity tomography and geophysical mapping techniques [22-26] for soil characterization. Established field testing protocols should be adapted for evaluating the performance of optimized bentonite-cement mixtures under various soil conditions. These studies will validate laboratory results and help to characterize real-world performance under different environmental conditions.

Another critical research direction is the investigation of long-term behavior. Although this study focused on 28-day properties to define optimal mixing ratios, extended monitoring over multiple years is needed to understand material performance under varying seasonal conditions [2]. It also involves evaluating the impact of repeated wetting-drying cycles, temperature fluctuations, and potential material degradation mechanisms on system performance.

Consideration of bentonite contents below 10% provide additional research opportunities to understand threshold effects on electrical and mechanical properties, develop low-cost installation methods, and seek modifications of materials that will enhance long-term stability. Also, economic analysis of different material combinations and installation techniques needs significant in-depth analysis to optimize the system's cost-effectiveness with reliable performance.

5. Conclusions

The results of this study show that cement pastes containing bentonite can potentially improve the electrical properties of cementitious materials for grounding systems in high-resistivity soils. Bentonite-based materials can effectively reduce grounding resistance, which has been shown in previous studies. Their chemical composition affects performance.

A key finding of this study is that, despite having significantly different chemical compositions (8.15% $\text{SiO}_2 + \text{Al}_2\text{O}_3$ for OPC and 15.02% $\text{SiO}_2 + \text{Al}_2\text{O}_3$ for NSG), the electrical behaviors of both materials were very similar after modification with bentonite. Specifically:

(i) Electrical resistivity decreased with increased bentonite content, most markedly at 30% replacement. However, this trend was consistent regardless of whether the materials had the same chemical composition (bentonite) or different base material chemistry, suggesting that the electrical properties were dominated by the bentonite content.

(ii) Compressive strength exhibited a systematic trend with bentonite addition, decreasing with increasing content for both materials. This behavior is consistent with previous studies on cement-bentonite composites. Our study is unique in showing this to be true across different cement types.

(iii) Electrical resistivity is correlated with moisture content in both materials with similar power law relationships despite their different chemical compositions. Consistency with previous findings confirms that our testing methodology is valid and extends the understanding to different cement types.

(v) A novel finding in this work is that OPC and NSG samples exhibit similar performance despite their different chemical composition, which builds on earlier work demonstrating the applicability of bentonite across cementitious matrices.

These results can be used to design grounding systems in high-resistivity soils. Our laboratory results demonstrate that bentonite modification can lead to similar electrical properties for both OPC and NSG, but NSG's potential advantage in dimensional stability requires further field validation. However, bentonite-modified cement pastes could achieve the required grounding resistance with fewer or smaller electrodes, although there is a trade-off between electrical and mechanical properties that must be carefully balanced for specific applications.

6. Acknowledgements

This research was supported by the National Science Research and Innovation Fund (NSRF) through Burapha University Fundamental Fund (Project No. 1.35/2568, fiscal year 2025).

7. References

- [1] IEEE. IEEE recommended practice for grounding of industrial and commercial power systems. IEEE Std 142-2007. USA: IEEE; 2007.
- [2] Androvitsaneas VP, Gonos IF, Stathopoulos IA. Performance of ground enhancing compounds during the year. 2012 International Conference on Lightning Protection (ICLP); 2012 Sep 2-7; Vienna, Austria. USA: IEEE; 2012. p. 1-5.
- [3] Zhang J, Xu L, Zhao Q. Investigation of carbon fillers modified electrically conductive concrete as grounding electrodes for transmission towers. *Constr Build Mater*. 2017;145:347-53.
- [4] Ou X, Ye G, Jiang J, Gong J, He Z. Improving electrical and mechanical properties of cement composites by combined addition of carbon black and carbon nanotubes and steel fibers. *Constr Build Mater*. 2024;438:136931.
- [5] Chung DDL. Electrically conductive cement-based materials. *Adv Cem Res*. 2004;16(4):167-76.
- [6] Hasan K, Jaya RP, Yahaya FM. Application of bentonite in cement-based composites: a review of current status, challenges, and future prospects. *J Build Eng*. 2024;98:111171.
- [7] Murray HH. Applied clay mineralogy: occurrences, processing, and application of kaolins, bentonites, palygorskite-sepiolite, and common clays. In: Murray HH, editor. *Developments in Clay Science*, Vol. 2. Amsterdam: Elsevier; 2006. p. 1-180.
- [8] Mohd Tadza MY, Mohamad D, Tripathy S, Rahman RA, Ismail MAM. Bentonite and marconite for electrical grounding applications from geotechnical engineering perspective. *AIP Conf Proc*. 2019;2129(1):020078.
- [9] Mohd Tadza MY, Tengku Anuar THH, Mat Yahaya F. Investigation on electrically conductive aggregates as grounding compound produced by marconite. *Civ Environ Eng Rep*. 2019;29(3):86-96.
- [10] Liu SY, Du YJ, Han LH, Gu MF. Experimental study on the electrical resistivity of soil-cement admixtures. *Environ Geol*. 2008;54(6):1227-33.
- [11] ASTM. ASTM C230/C230M-23: Standard specification for flow table for use in tests of hydraulic cement. West Conshohocken: ASTM International; 2023.
- [12] Presuel-Moreno F, Wu YY, Liu Y. Effect of curing regime on concrete resistivity and aging factor over time. *Constr Build Mater*. 2013;48:874-82.
- [13] ASTM. ASTM C1876: Standard test method for bulk electrical resistivity or bulk conductivity of concrete. West Conshohocken: ASTM International; 2023.
- [14] AASHTO. Standard method of test for surface resistivity indication of concrete's ability to resist chloride ion penetration (TP 95). Washington DC: AASHTO; 2011.
- [15] ASTM. ASTM C39/C39M: Standard test method for compressive strength of cylindrical concrete specimens. West Conshohocken: ASTM International; 2019.
- [16] ASTM. ASTM D2166/D2166M: Standard test method for unconfined compressive strength of cohesive soil. West Conshohocken: ASTM International; 2019.
- [17] ASTM. ASTM D4959: Standard test method for the determination of moisture content of soils by direct heating. West Conshohocken: ASTM International; 2000.
- [18] Lim SC, Gomes C, Ab Kadir MZA. Electrical earthing in troubled environment. *Int J Electr Power Energy Syst*. 2013;47:117-28.
- [19] Vincent NA, Shivashankar R, Lokesh KN, Jacob JM. Laboratory electrical resistivity studies on cement stabilized soil. *Int Sch Res Notices*. 2017;2017:8970153.
- [20] Turan E, Oltulu M. The effect of calcined bentonite clay on the late-age electrical conductivity of cement paste after wetting and drying cycles. *Int J Adv Nat Sci Eng Res*. 2023;7(9):7-11.
- [21] Arjwech R, Phothaworn T, Chaisuriya S, Thitimakorn T, Pondthai P. Evaluation of slope susceptibility using 2D electrical resistivity tomography supplemented with spatial resistivity change. *Geotech Geol Eng*. 2023;41(7):4023-39.
- [22] Arjwech R, Hongsresawat S, Chaisuriya S, Rattanawanee J, Kanjanapayont P, Youngme W. Identification and verification of the movement of the hidden active fault using electrical resistivity tomography and excavation. *Geosciences*. 2024;14(8):196.
- [23] Samtina T, Arjwech R, Everett ME. Geophysical mapping of shallow rock salt at Borabue, Northeast Thailand. *Near Surf Geophys*. 2019;17(4):403-16.
- [24] Arjwech R, Everett ME. Sinkhole formation induced by descending groundwater in a karst aquifer near a limestone quarry. *Earth Surf Process Landf*. 2024;49(15):5027-37.
- [25] Tamasa S, Arjwech R, Eua-Apiwatch S, Nulay P. Characterizing quaternary terrace sediments in gravel pits: a study using lithology, electrical resistivity tomography, and induced polarization methods for preserving petrified wood as a geoheritage site and safeguarding groundwater environments. *Geoheritage*. 2024;16(4):116.
- [26] Tucker SE, Briaud JL, Hurlebaus S, Everett ME, Arjwech R. Electrical resistivity and induced polarization imaging for unknown bridge foundations. *J Geotech Geoenviron Eng*. 2015;141(5):04015008.