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ADVANCING ELECTRICAL GROUNDING SYSTEM: AN ANALYSIS OF NATURAL AND COMPOSITE MATERIAL FOR ENHANCED PERFORMANCE

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Abstract:

Electrical grounding systems for power systems are among the most vital means for fault current dissipation while preventing dangerous step and touch voltage gradients. It can also significantly affect the reliability and safety of the electrical systems. Grounding Enhancement Materials (GEMs) have been one of the pivotal components for optimizing the behavior of grounding systems in locales with increased soil resistivity or less-than-optimal environmental conditions. This review provides an overview of recent developments in GEMs based on conductive materials, such as bentonite, carbon-based composites, metal oxides, and unique electroactive and nanostructured polymers. It discusses their electrical, thermal, and environmental properties, emphasizing resistivity reduction, longevity, and environmental compliance. In addition, the review critiques existing GEM performance evaluation techniques at both lab-scale and field-scale conditions, as well as predictive models for GEM performance, such as linear regression and machine learning methods. Hurdles such as material degradation, environmental leaching, and cost-effectiveness are also covered to offer a neutral view of the present constraints and future perspectives. Lastly, the review focuses on some trends associated with sustainable and high-performance GEMs, showcasing the renewable opportunities of bio-based and hybrid materials by bottom-line green engineering principles. Overall, the synthesis is intended to share knowledge in selecting, designing, and implementing GEMs to enhance the efficiency and sustainability of various electrical systems that use grounding systems across applications.

Keywords:

Alternating Current (AC), Conductive Material, Electrical System, Grounding System, Grounding Enhancement Material (GEM), High Voltage Alternating Current (HVAC), High Voltage Direct Current (HVDC), Natural Enhancement Material (NEM).

Introduction

One of the countries with high lightning activity is Malaysia, which is situated near the equatorial region, with an annual number of thunderstorm days of about 180 to 260 per year. This logistical intensity leads to one of the most populous lightning flash densities on the planet, threatening infrastructure, life, and livelihoods and implementing economic impacts.. The total cost to the national economy is enormous due to damage caused by lightning to electrical and electronic systems, power outages, and deaths. Petronas twin towers, Kuala Lumpur City Center (KLCC), and KLCC Skyline are architectural wonders and serve as Malaysia's largest lighting surge arrestor. Using the newest lightning protection technology, these towers mitigate the threat of the city's frequent storms, both to the towers themselves and the densely populated urban area in which they are located.

The unique fact is that even while the incidence of lightning is much greater, Malaysia still persists in pursuing urbanization, and vertical expansion for lightning protection and grounding systems will inevitably be required. Different types of soil characterize the country's tropical climate. However, in some places, the resistivity of the soil is high, which negatively affects the performance of the grounding system. Another major factor could be improper grounding, which leads to a discharge of currents accumulated from a lightning storm in a building or electrical installation falling short, thereby increasing the risk of breaking by lightning. Collectively, these underscore the significance of sound grounding systems, which enable the safe operation of electrical systems by letting fault currents and lightning surges flow safely to Earth.

Correspondingly, Grounding Enhancement Materials (GEMs) have become the primary method of improving grounding performance, especially under unfavorable soil conditions. These materials' conductive backfills, gels, and compounds assist in making the soil surrounding the ground electrodes more electrically conductive to dissipate electricity from grounding electrodes effectively. Furthermore, grounding system resistance mitigation, long-term stability, persistence, and enhancing an electronic system of device stability. Interestingly, some developments in this area also seek to make it a greener endeavor by utilizing ground enhancement materials that improve performance while minimizing ecological footprint.

This paper will further review different enhancement materials (Parise et al., 2018) used to enhance grounding system performance globally. In particular, it will address their properties, their mechanisms of action, how they are formulated, and how well they perform under different environmental conditions. In addition, researching existing technologies will offer insights into improving the system to make the components in the grounding system safe and reliable. This is vital in countries like Malaysia, where there are high concentrations of

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lightning strikes, and reliable earthing is essential in terms of safety for both infrastructure and human life.

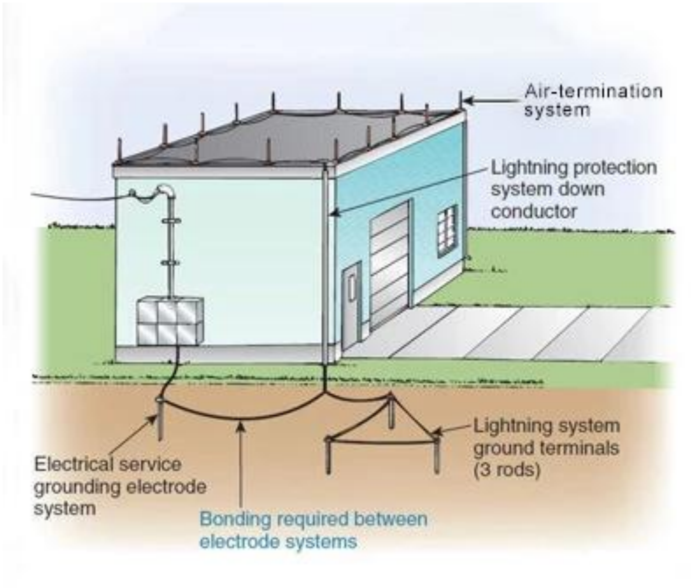

Figure 1: Grounding System in Building

Source: Rouibah et al. (2012)

Improve The Materials for Grounding Systems

GEMs (Azmi et al., 2019) are specifically designed to improve the electro-physics of the Earth. They lower the resistivity of the soil (Androvitsaneas et al., 2020), making it easier for fault currents to dissipate. Over time, many materials have been developed, ranging from natural materials to waste products from industry and agriculture. This all comes with pros and cons and the most recent material types. As such, there are (very) roughly three categories of terrestrial lumbering accouterments (Wahba et al., 2023). This first group of natural materials is derived from organic and natural resources. Meanwhile, the latter are chemical materials devised using alternate inorganic processes to enhance conductivity and performance. At the same time, the third group of materials, waste, includes those produced as by-products in industries, agriculture, construction, and demolition. Notably, reusing these wastes in grounding systems is an eco-efficient and sustainable solution. These categories are incorporated with several products to improve grounding systems' working and reliability.

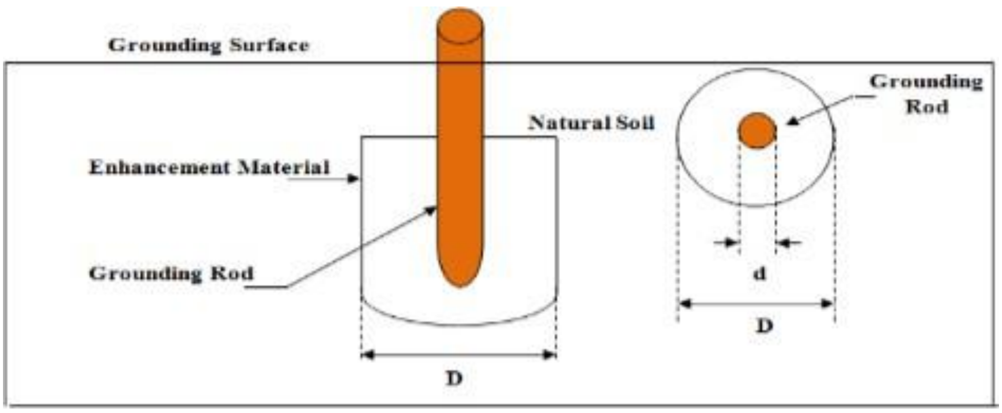

Figure 2: Enhancing Material into Soil and Around the Rod

Source: Wahba et al. (2023)

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Natural Organic Materials

Table 1: Measured Earth Resistance Value Throughout the Work

Grounding System	Day-0 Earth Resistance (Ω)	Highest Earth Resistance		Lowest Earth Resistance	
		Earth resistance (Ω)	Day-n	Earth resistance (Ω)	Day-n
Bentonite + Kenaf Powder Layered	26.20	27.50	1	24.50	36
Bentonite + Kenaf Powder Mixed	25.60	28.70	52	25.10	21
Bentonite + Kenaf Fibre Layered	31.00	32.40	2	27.40	36
Reference	62.10	71.10	52	58.80	27

Source: Wan Ahmad et al. (2018)

Four grounding systems were utilized (Khurshid & Gomes, 2021) to maximize the earth resistance reduction potential of bentonite and kenaf mixtures used as Natural Enhancement Materials (NEMs). Specifically, the three systems contained different arrangements of bentonite, and kenaf powder layered, powder mixed, and fiber layered, while the fourth represented a reference without any NEM. Simultaneously, field execution was performed for 60 days at Universiti Putra Malaysia, and fall-of-potential measured earth resistance with a 0° separation angle between current and voltage probes. Accordingly, the best reduction in earth resistance was achieved with the layered bentonite and kenaf powder system, which was much lower than the other two systems and the reference system. Meanwhile, the effect of ambient temperature on resistance reduction was modest, and applying these NEMs left no dangerous environmental footprint. In summary, the study suggests that the bentonite and kenaf powder layered grounding system is an efficient method for grounding soil treatment, and further exploration of mixture ratio optimization for grounding needs to be conducted in the near future.

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Natural Mineral Materials

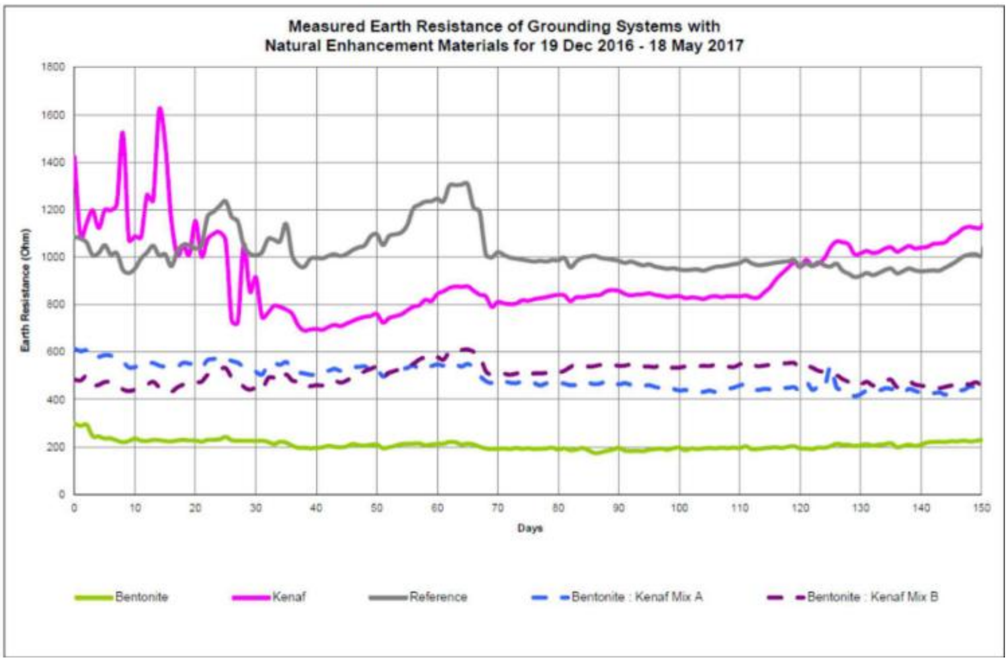

Figure 3: Measured earth resistance for NEM mixture grounding systems with Bentonite and Kenaf from Dec 2016 until May 2017

Source: Wan Ahmad, Mohamad Roslan, et al. (2023)

Electrical breakdown properties of bentonite, laterite ores, bauxite, and china clays as a potential walkaround to grounding realism underneath rotating and direct stream conditions. The laterite-bentonite mix demonstrated the highest performance of assessed mixtures in the presented work, and an increase in 41% performance was calculated compared to other mix samples in AC (Ahmad, Kassas, et al., 2021). Compared to VOLT, equal-breakdown voltages of monolayer/multilayer sheets are evaluated.

Due to their fast kinetics, the proportion of laterite-bentonite mixtures exhibits significantly lower values under DC conditions than those of bentonite alone, with reductions of 46% and 36% of the laterite green and red materials, respectively. For bauxite-bentonite mixtures, the breakdown voltage under AC was 34% lower. Simulation and experimental studies confirm that a better electrical characteristic should allow the exploration of these mineral compounds for portable and low-maintenance grounding applications.

Chemical Salts Materials

The previous research examines the temporal performance impact of Chemical Enhancement Materials (CEMs) on grounding systems (Ahmad et al., 2010). According to the results, an increase in the application of CEMs time causes a reduction of grounding resistance in a ratio way. Eventually, the steady state of resistance was reached by completing within 21 days. Although the best performance as a CEM was achieved by NaCl, as compared to the reference system, NH_4Cl performed poorly, with the lowest resistance achieved by day 141. These findings promote NaCl as an advised CEM for grounding systems, especially for lightning protection conditions. Following this, the results from this study form a basis for determining suitable CEMs for steady-state performance in embedding systems.

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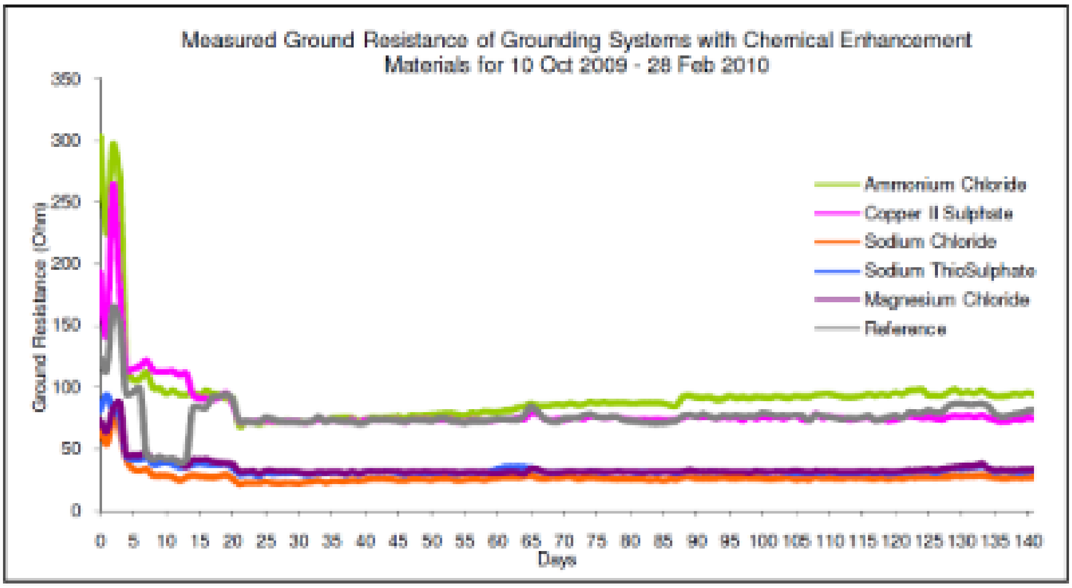

Figure 4: Measured Ground Resistance of Grounding Systems with Chemical Enhancement Materials for Oct 2009-Feb 2010

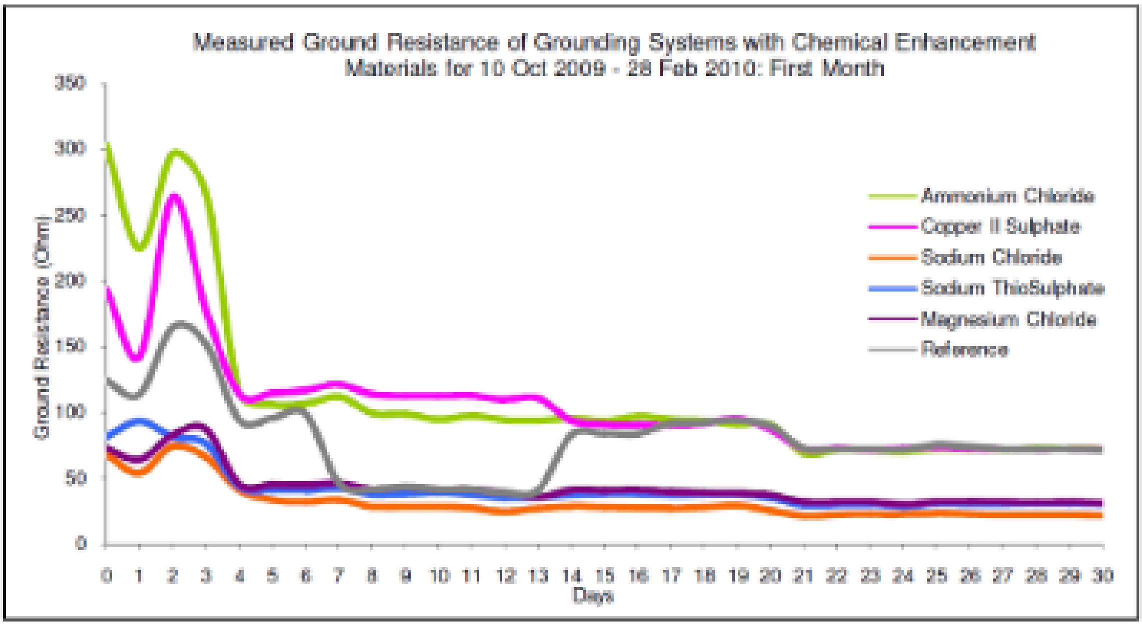

Figure 5: Measured Ground Resistance of Grounding Systems with Chemical Enhancement Materials for Oct 2009-Feb 2010 during the First Month

Agricultural Waste Materials

The research (Bakar et al., 2022) examined the possibility of kenaf core blended with clay as a natural improvement material in reducing ground resistance. Several High Voltage Alternating Current (HVAC) / High Voltage Direct Current (HVDC) tests for breakdown voltage and conductivity were performed using mixtures containing different amounts of kenaf. Moreover, results reveal that kenaf has a high-conductive value, and the lower value of breakdown voltage is obtained when the percentage of kenaf is less. The test included a ten-second duration of high voltage application to the device, with material conditions (i.e., wet/dry), temperature, and relative humidity being monitored. In addition, this study demonstrates that the studied kenaf is a practical natural improvement material for grounding systems due to its satisfactory level of conductivity and reliability.

Table 2: Table of Ground Enhancement Material in Reducing Grounding Resistance and Cost Involved from previous work

Soil-Enhancement Material	Type	Cost	Grounding Resistance Reduction
Bentonite and Kenaf (Powder Mix) (Wan Ahmad, Mohamad Roslan, et al., 2023)	Natural	Low	41.66% reduction over 150 days
Bentonite and Peat Moss (Mix A) (Wan Ahmad, Abdul Rahman, et al., 2023)	Natural	Low	20.17% reduction compared to the reference
Fly Ash and Wood Ash Mixture (Ahmad et al., 2018)	Waste	Low	28.96% reduction over 130 days
Sodium Chloride (NaCl) (Ahmad et al., 2010)	Chemical	Low	Best performance after 141 days
Kenaf and Clay Mixture (Abu Bakar et al., 2022)	Natural	Low	High conductivity observed; reduction depends on the mixture ratio
Bentonite and Zeolite Mix (Wan Ahmad, Abdul Rahman, et al., 2023; Wan Ahmad, Mohamad Roslan, et al., 2023)	Natural	Low	Superior performance over 150 days
Laterite and Bentonite Mixture (Ahmad, Sabry, et al., 2021)	Natural	Low	41% improvement under AC conditions
Bauxite and Bentonite	Natural	Low	34% lower breakdown voltage under

Laboratory Testing Methods

Soil Box Method
The resistivity of GEMs is commonly measured using the soil box technique, in which GEMs are mixed together with soil specimens. A standard soil box system consists of a rectangular box with electrodes in specific intervals. Inside the box, the GEM-soil mixture is compacted, and an electrical current is applied through the outer electrodes. This directly measures the voltage drop across the inner electrodes, and Ho's law, combined with the geometrical factors of the box, enables the calculation of resistivity.

Four-Point Wenner Method
This technique (Sazali et al., 2020) consists of inserting four equally spaced probes into the GEM-soil sample. An AC is then injected through the outer probes, and a potential difference is measured between the inner probes. The resistivity is determined by the probe spacing, and

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the voltage and current are measured. Subsequently, the new method minimizes the influence of contact resistance and allows in-situ or laboratory measurements, respectively.

Moisture Content Analysis

Moisture (Wan Ahmad, Mohamad Roslan, et al., 2023) is a significant factor affecting the electrical conductivity of GEMs. In lab tests, GEM samples are placed into different moisture conditions, and the resistivity is measured. In the gravimetric approach, the samples are weighed both pre and post-oven-drying, and the difference in masses determines the moisture content. This relationship between moisture content and resistivity is vital in understanding the performance of GEMs under different environmental conditions.

Chemical Composition Analysis

In order to predict the long-term behavior and environmental impact of GEMs, knowledge of their chemical makeup (Ahmad et al., 2010) is crucial. Methods for elemental quantification include X-ray Fluorescence (XRF) and Inductively Coupled Plasma-Mass Spectrometry (ICP-MS). Environmental samples undergo analysis for contaminants and compliance with environmental regulations.

Leachate Testing

Leachate testing assesses the risk of toxic (Ahmad et al., 2010) compounds leaching from GEMs into soil and groundwater. The Toxicity Characteristic Leaching Procedure (TCLP) is a standardized approach where GEM samples are leached with a leaching solution under specific conditions. The leachate is then treated for heavy metals and contaminants analysis using Atomic Absorption Spectroscopy (AAS) or ICP-MS techniques.

Mechanical Strength Testing

Mechanical strength is a fundamental property for GEMs that is capable of forming solid masses like conductive concretes. Universal testing machines are used for compressive and tensile strength tests. Subsequently, samples are prepared in fixed shape and size, and the load is applied until failure. Thermal and mechanical tests ensure the GEM's robustness against installation and operational-induced mechanical stress.

Corrosion Rate Measurement

GEMS are directly in contact with grounding electrodes, which raises the issue of their corrosivity (Ahmad et al., 2010). Various electrochemical methods (Linear Polarization Resistance (LPR) and Electrochemical Impedance Spectroscopy (EIS), to name a few) are frequently employed to determine the corrosion rate of the metals in contact with the GEMs. Such tests assist in material selection to reduce corrosion and enhance the longevity of grounding systems.

Testing for the Environmental Durability

The performance of GEMs (Bagaskara et al., 2023) may be influenced by environmental (Ahmad, Sabry, et al., 2021) factors such as temperature changes, freeze-thaw cycles, and wet-dry cycles. Note that accelerated aging tests replicate these conditions in the lab. Samples undergo a series of cycles, and their properties are measured pre- and post-testing to determine durability.

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Field Testing of Grounding Enhancement Materials

Field testing (Stanišić & Radaković, 2023) is fundamental in evaluating GEMs in grounding systems. Field tests, on the other hand, reflect the conditions in which GEMs might perform in practice and demonstrate how real-world variables like environment and use affect their operation and performance. Testing is critical to ensure that laboratory findings hold up, regulatory compliance is achieved, and long-term performance can be assessed.

In-Situ Readout of Resistivity

Field tests for electrical resistivity are usually conducted using the four-point Wenner method (Stanišić & Radaković, 2023). This method embeds probes at the soil-GEM junction at the installation site, and then AC is applied. Simultaneously, voltage and current measurements are used to compute resistivity, considering local soil heterogeneities and the GEM's interaction with the native environment. This approach is instrumental in deriving resistivity over the range of moisture and temperature that closely represents hydrous states and site-specific performance.

Contact Resistance Evaluation

A significant part of field tests evaluates the contacting resistance between GEMs and grounding electrodes (Stanišić & Radaković, 2023). High contact resistance could limit fault currents. In practice, such field techniques are based on the sequential application of low-frequency AC and subsequent records of potential drop/s at the interface. At the same time, fall-of-potential testing or clamp-on resistance meters are used to confirm performance validation of GEMs in retaining low resistance during their full operational lifespan.

Over the Long Term Evaluate Performances

Field monitoring systems are furnished to monitor GEM durability and stability through time. Such systems track critical parameters like resistivity, soil pH (Bakar et al., 2022), and moisture levels. The collected data aid in current evaluations of how environmental changes, including seasonal cycles of moisture and temperature, may impact GEM performance. Long-term studies also allow for the effects of degradation and any change in the material's properties to be detected.

Corrosion Testing

The hardware used in GEM (Ahmad et al., 2018) tests also involves field testing to examine the corrosive behavior of GEMs in contact with metallic electrodes. In situ corrosion monitoring techniques include LPR and EIS. These tests examine the corrosion rate of electrodes used to guarantee that these poles are compatible with the GEMs and their surrounding environment, prolonging the life of the grounding system.

Use Cases – Validation of Environmental Durability

The performance of GEM is heavily influenced by environmental factors like freeze-thaw cycles, wet-dry cycles, and soil contamination (IEEE Centro Occidente Section et al., 2018). Field testing under such conditions consists of fitting GEM-inspired grounding systems in environments susceptible to extreme environmental pressures (e.g., high humidity, standing water) to verify the hypothesis. Previous observations have been made to measure material properties, resistivity, and mechanical integrity variation. For example, accelerated testing in

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the field may also implement artificial wetting or temperature cycling to simulate years of use in a few months.

Testing Site-Specific adaptability
Soil type (clay, sandy, rocky) (Qahtani, 2009; Ahmad, Sabry, et al., 2021) can significantly affect the effectiveness of a GEM. The next stage is field testing, such as adaptability tests, which assess how well the material performs under various geotechnical conditions. This includes examining GEM-soil interactions, compaction quality, and moisture retention capability. The results of these studies help in selecting the best GEM composition for a specific site.

Analysis of The Impedance of the Grounding System
Impedance analysis (Kostić, 2021) under field conditions can help understand the GEM high-voltage grounding system's overall performance. Methods such as the Sweep Frequency Impedance Method (SFIM) analyze the system's behavior over a spectrum of frequencies, maintaining it within limits during steady-state and transient fault conditions.

Design Grounding System With Enhancement Material Using Wenner's Four Pin (WFP)
Wenner's four-pin method accurately measures soil resistivity (Sazali et al., 2020) and is necessary for designing effective grounding systems. It is also the key to optimizing the grounding performance. Outside the electrodes are the four same-length and evenly separated electrodes (Stanišić & Radaković, 2023). Two outer electrodes push current (III) while the inner Electrodes measure the resulting voltage (V), which can be employed to infer detailed information underneath).

Soil resistivity is determined by Radakovic et al. (2015):

$$\rho = 2\pi a \frac{V}{I},$$

where α is the distance between electrodes, the first step is a site survey using different spacings between the electrodes (e.g., 1 m, 2 m, 5 m), creating a detailed resistivity profile to locate the areas needing corrective grounding. If any grounding electrodes are to be installed, they are usually made of a corrosion-resistant material, copper or galvanized steel. Furthermore, vertical rods can penetrate deeper layers in low-resistivity regions, and in high-resistivity areas, horizontal grids or additional rods may be needed. In addition, to improve soil resistivity under challenging areas, enhancement materials like bentonite (which expands out, increasing the area in contact), coke breeze (a conductive form of carbon), or chemical salts such as calcium chloride are used. Such materials enhance the conductivity and the efficiency of the grounding system as a whole. In line with this, testing soil resistivity, electrode conditions, and fill-in enhancement materials is vital for long-term performance and control. Thus, by minimizing soil variability and considering this when designing, the Wenner method guarantees a conservative and robust solution to ensure that the grounding system may efficiently and effectively dissipate fault currents in many ground conditions. This is especially effective for industrial, renewable energy, and lightning protection applications.

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Evaluation of Using Enhancement Material in Grounding System

Low ground resistance is critical in high-resistivity soils. Materials like bentonite (Wan Ahmad, Mohamad Roslan, et al., 2023), clay (Abu Bakar et al., 2022), graphite, and conductive concrete can enhance soil conductivity in the surrounding grounding electrode. The review paper also investigates how these products decrease ground resistance, soil kind, ecological effect, durability, and price. Note that improvement of ground resistance with enhancement materials increases system reliability. Therefore, adopting and using additives must be cautious, yet optimizing performance while respecting ecological and economic aspects is essential.

Findings

Table 3: Main Findings of Research Paper

No.	Research Component	Findings
1	Research Gaps	Limited research on transient impulse performance of grounding systems (e.g., lightning strikes). Inadequate investigation on fulgurite formation (soil fusion into glass-like structures from lightning) and its effects on grounding impedance. Insufficient evaluation of long-term environmental impacts, particularly chemical leaching and corrosion in different soils. Few studies systematically optimize the mixture ratios and placement strategies of GEMs. Limited practical validation of GEM performance across varied geographical and climatic conditions. Lack of comprehensive standards or guidelines universally applicable for GEM usage.
2	Types of Enhancement Materials	Natural Organic: Bentonite, Kenaf powder, Kenaf fiber. Natural Mineral: Bentonite, Laterite ores, Bauxite, China clay, Zeolite. Chemical Salts: Sodium Chloride ($NaCl$), Ammonium Chloride (NH_4Cl). Agricultural and Industrial Waste: Kenaf core, Fly ash, Wood ash, Peat moss.
3	Type of Soil Enhancement Material	Natural: Bentonite, Kenaf, Peat Moss, Zeolite, Laterite ores, Bauxite, China clay. Chemical: Sodium Chloride ($NaCl$), Ammonium Chloride (NH_4Cl). Waste-based: Fly Ash, Wood Ash.

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4	Advantages of Research	Demonstrated that the use of bentonite and kenaf significantly reduces earth resistance by up to 41.66% over 150 days. Provided clear environmental and cost-effective benefits using natural and waste based materials. Established that natural materials, especially bentonite mixtures, retain moisture, enhancing grounding performance during dry periods. Developed optimization methodologies to balance performance and economic feasibility. Emphasized sustainability and minimized ecological footprint through eco-friendly GEMs like wood ash and kenaf mixtures. Improved system reliability and reduced maintenance through effective GEM integration.
5	Future Recommendations for Future Works	Conduct studies focusing on transient impulse (lightning) performance to ensure grounding robustness. Investigate fulgurite formation and its implications for grounding system performance. Examine long-term environmental durability, specifically chemical leaching, corrosion, and degradation under diverse conditions. Validate findings through broader geographical and climatic field tests. Develop universal guidelines and standards for GEM usage applicable globally. Explore further optimization techniques, specifically machine learning, to determine the best GEM configurations for varying soil and climate conditions. Conduct laboratory impulse testing and monitor real-world lightning events to validate theoretical and experimental results.

Conclusion

The previous findings underscore that grounding impedance is a dynamic parameter strongly influenced by environmental conditions, particularly seasonal fluctuations in soil moisture and temperature. Through extensive field measurements and simulations, it was observed that soil resistivity and, hence, grounding impedance varies significantly between wet and dry seasons and with temperature changes in the subsurface. Moreover, this critical insight highlights that effective grounding system design must account for temporal changes in soil conditions. A system optimized for the rainy season could perform sub-optimally in a drought and vice

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versa. Additionally, by recognizing the seasonal variability in grounding performance, the research establishes a foundational understanding that any long-term, high-reliability grounding solution must maintain low impedance across the range of expected climatic conditions.

To address these challenges, the study systematically classified soil enhancement materials into three categories: natural, chemical, and novel waste-based materials, each offering distinct performance benefits for grounding improvement. This classification provides a structured perspective on available enhancement options. Remarkably, natural materials (exemplified by bentonite clay) were demonstrated to retain moisture and reduce soil resistivity, thereby keeping grounding impedance low even during extended dry periods. At the same time, chemical additives (such as conductive salts or gels) can initially achieve very low resistances, and the research discusses their efficacy alongside concerns like leaching and corrosion over time. Notably, novel waste-based materials emerged as a promising category for sustainable engineering: for instance, wood ash, a by-product of biomass combustion, demonstrated notable benefits by introducing conductive mineral content to the soil and improving moisture retention. The experiments confirmed that bentonite significantly enhances grounding performance by swelling with water and maintaining contact between the electrode and soil. Moreover, wood ash provided an eco-friendly alternative that achieved up to comparable impedance reduction by recycling waste into a functional backfill. By comparing these materials, the dissertation highlights that judicious selection and blending of enhancement materials can mitigate the impact of seasonal drying, stabilize grounding impedance year-round, and even offer environmental and economic advantages.

Equally crucial is the role of optimization methodologies in designing cost-effective, high-performance grounding configurations. The research incorporated advanced optimization techniques to determine the optimal mix and placement of enhancement materials and electrode configurations that yield the lowest possible impedance for a given cost constraint. This approach considered multiple variables, material proportion, and layer thickness to electrode depth and spacing, and identified solutions that balance performance with practicality. The results demonstrate that employing a formal optimization framework is invaluable: engineers can achieve substantial impedance reduction (improving safety margins) without undue cost or material usage. In practical terms, this suggests that enhancements like bentonite or wood ash can be optimized to maximize their benefit-to-cost ratio, making improved grounding systems economically feasible for broad deployment. This dissertation catalogs effective materials and provides a decision-making methodology to optimally apply those materials in the field, ensuring that improvements are technically sound and financially justified.

While enhanced grounding systems steady-state and seasonal performance are well characterized in this work, further studies under transient impulse conditions are recommended to ensure system robustness fully. Accordingly, real-world grounding systems must endure high-energy events like lightning strikes, where current surges can cause soil ionization and even physical transformation. A notable phenomenon of interest is the formation of fulgurite, the fusion of soil into a glass-like substance due to lightning's extreme heat. Correspondingly, this research raises the point that fulgurite formation around electrodes, if occurring, could markedly increase local soil resistivity by creating an insulating barrier, thereby degrading the grounding effectiveness after a strike. As such, a prudent

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extension of this research is to investigate how different enhancement materials and configurations behave under lightning impulses and whether they can withstand or mitigate the effects of soil fusion. Furthermore, understanding the interplay between enhancement materials and impulse conditions (surge currents, rapidly changing fields) will translate the benefits observed under normal conditions to all-weather, all-event reliability. It is recommended that future work includes laboratory impulse tests and field measurements during actual lightning events to assess transient performance, quantify any impedance changes post-strike, and develop strategies (if needed) to prevent or accommodate fulgurite formation. In essence, the longevity and reliability of grounding improvements can be assured even under the most extreme electrical stress events.

The insights from this research have broad global applicability and carry significant practical implications for improving electrical infrastructure safety and reliability worldwide. The materials classification and optimization framework developed here can be adapted to diverse soil types and geographic regions. Whether the grounding system is in the arid soils of desert regions, the lateritic clays of the tropics, or the permafrost-affected ground of high latitudes, the core principles remain relevant. This includes understanding local soil behavior, selecting appropriate enhancement materials, and optimizing their use, which can dramatically improve grounding performance. Additionally, future collaborations with international research and standardization bodies are encouraged to apply and validate these findings across different climates and soil chemistries, ensuring the recommendations are universally robust. The outcome would be a set of best practices or guidelines that help engineers worldwide implement low-impedance, stable grounding systems regardless of location. This is a significant step toward harmonizing safety standards across the global power industry.

This research provides a comprehensive analysis and methodology for enhancing grounding systems, bridging the gap between theoretical soil-electrode behaviour and practical engineering solutions. Notably by revealing how seasonal environmental factors influence grounding impedance and how targeted use of natural, chemical, and waste-based enhancement materials (notably bentonite and wood ash) can counteract these effects. This is coupled with an optimization strategy to guide efficient implementation, and the research delivers both new knowledge and actionable techniques for the field of electrical engineering. The findings and recommendations, especially regarding transient performance and worldwide application, pave the way for next-generation grounding practices. Ultimately, adopting these insights in real-world electrical infrastructure will lead to safer, more efficient, and more reliable grounding systems, enhancing the protection of equipment and human life from electrical faults and lightning surges and contributing to the resiliency of power systems globally.

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