

Design, Development, and Experimental Evaluation of Marble Spool Insulator

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ABSTRACT

Spool insulators made of either porcelain or polymer are widely used in insulating electrical components in secondary electrical wires and are typically imported. The Philippines should capitalize on producing spool insulators using locally available materials such as marble, with promising potential due to its abundance, mechanical durability, hydrophobic properties, and environmental sustainability. Thus, this study aimed to design, develop, and test marble spool insulators. Three (3) different marble materials categorized by color were used and designed using the ANSI 53-2 standard. The prepared marble spool insulators were electrically tested using an impulse flashover voltage test, while physical properties like wettability and abrasion resistance were also determined. Impulse flashover voltage test results revealed that all marble spool insulators exhibited high electrical resistance to voltages up to 30 kV, while the contact angle test showed that marble spool insulators are more hydrophobic ($\theta \geq 60^\circ$) than the porcelain spool insulator ($\theta = 0^\circ$). Moreover, abrasion loss is 4.85% greater than marble's, suggesting that marble is more durable than porcelain. The study demonstrates the viability of using marble for spool insulator fabrication, showcasing its superior electrical resistance, hydrophobicity, and durability compared to porcelain. This presents an opportunity for local production, reducing dependence on imports and opening new market prospects in the electrical insulation industry. However, further market research and validation tests are needed to compete with commercial porcelain spool insulators.

Keywords: *marble, marble spool insulator, impulse flashover, wettability, abrasion test*

INTRODUCTION

Efficient and reliable electrical power transmission across vast distances critically depends on the design and functionality of overhead transmission lines, where insulators are essential components (Han et al., 2009). These insulators prevent the unwanted flow of electrical currents from conductors to the earth, safeguarding the integrity and efficiency of the power transmission system (Tongse et al., 2023). Among various materials employed for this purpose, porcelain (Han et al., 2009), made from clay (Orovwode et al., 2024), silica, kaolin, and feldspar emerge as a prominent choice due to their superior insulating properties (Ologunwa et al., 2021; Tongse et al., 2023). The effectiveness of this material is attributed to its ability to be molded into various

shapes and sizes. Its high dielectric strength and minimal water absorption ensure durability and resistance against environmental stressors like weather, acid fumes, or gases (Kempton, 1910).

The distinction between the types of insulators (e.g., pin, post, shackle) and the materials from which they are made (e.g., glass, porcelain) is crucial for understanding their applications and functionalities within the transmission system (Ologunwa et al., 2021). This paper aims to critically analyze the optimal particle sizes of porcelain's constituent materials, with the intention of enhancing the insulating efficiency of overhead transmission lines.

Moreover, the production of insulators made from porcelain and plastic is energy-intensive and contributes significantly to greenhouse gas emissions, primarily due to high-temperature firing and long processing cycles (Ibn-Mohammed et al., 2019). These environmental concerns necessitate the use of alternative materials that meet both performance and sustainability standards. In line with circular economy principles, recent research promotes the repurposing of locally available and underutilized materials for engineering applications (Kirchherr et al., 2017). One such material is marble,

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Received 16 April 2025; Revised 15 July 2025; Accepted 5 December 2025



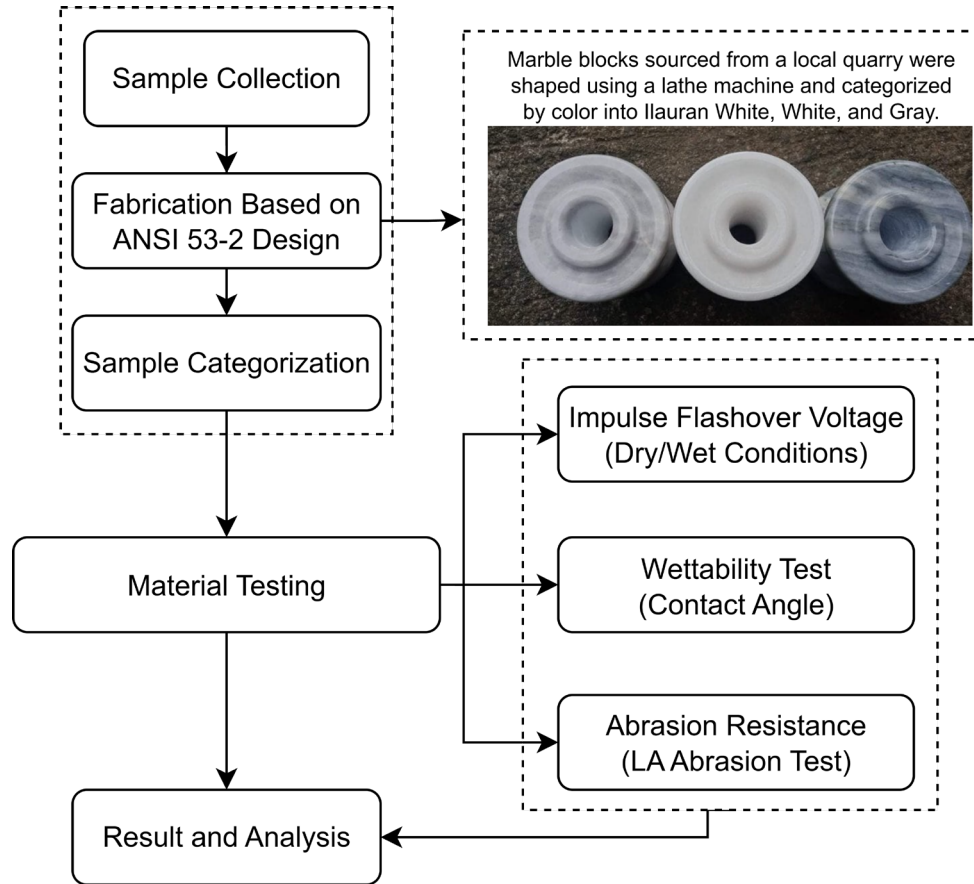


Figure 1. Sequential Methodology

which is abundant in Romblon, Philippines, and traditionally used in construction. Its dense structure, mechanical durability, and hydrophobic properties offer promising potential for electrical insulation. Utilizing local marble not only reduces reliance on imports but also supports regional industry and sustainable development (Gacu & Sim, 2022).

The context of local materials and industries, such as the marble industry in the Philippines' Romblon municipality, underscores the potential of local resources in various applications (Senoro et al., 2022). While marble is primarily associated with construction and decoration, the extraction and processing practices in regions with abundant natural resources illustrate the broader implications of material selection in industrial applications (Forcado & Estrada, 2018; Gacu & Sim, 2022; Senoro et al., 2022). Although extensive studies have been conducted on porcelain and polymer insulators, there is a noticeable absence of literature on the use of marble as an insulating material. The lack of prior research results in limited data on the design applicability, performance behavior, and field validation of this system, especially under tropical and humid conditions. This study aims to address this gap by

pioneering the evaluation and design of marble spool insulators based on international standards.

This study addresses the lack of research on alternative materials for spool insulators by exploring the potential of marble to improve the performance and sustainability of existing porcelain-based designs. The study aims to design, develop, and test marble spool insulators. Specifically, it aimed to design and develop a marble spool insulator conforming to a standard specification and to determine the electrical properties of the marble spool insulator in terms of horizontal and vertical impulse flashover voltage, as well as its physical properties in terms of wettability and abrasion resistance.

MATERIALS AND METHODOLOGY

Fabrication of the Marble Spool Insulators. The study determined that the design of the spool insulator is based on ANSI 53-2, as specified in ANSI/NEMA C29-3, for wet-process porcelain insulators (spool type), as it is the most widely used and available in the local market. Rectangular-shaped blocks of marble rock were



Figure 2. Various colored Marble Spool Insulators bearing the patent code PH 2/2020/050891.

obtained from local quarry sites and formed into a design specified using a lathe machine, with a smooth finish surface achieved by buffing. Three (3) types of marble spool insulators were fabricated according to color: Ilauran white, white, and gray.

Material Testing and Characterization. The prepared marble spool insulators and another porcelain spool insulator sample were tested according to their electrical (impulse flashover voltage) and physical properties (wettability and abrasion).

Impulse Flashover Voltage Test. An HRHGV-30 kV lightning impulse generator was utilized to conduct impulse flashover voltage tests. The equipment was configured in automatic mode, with the maximum voltage set to 30 kV to mimic lightning strikes. Each sample, including porcelain spool insulators, was firmly affixed vertically and horizontally onto dedicated sample holders. These tests aimed to ascertain the sample's ability to withstand lightning pulses perpendicular to its surface.

To assess the impact of moisture on resistivity, one batch of samples was sprayed with distilled water before testing, while another batch remained dry throughout the testing process. This procedure evaluated variations in flashover performance under different moisture conditions. The test setup and execution adhered to established protocols to ensure accurate and reliable results (Zhang et al., 2018). Furthermore, Kalenderli et al., 2003 emphasize the importance of comparing insulators for impulse voltages, highlighting criteria such as high breakdown strength, dielectric constant, low costs, and ease of maintenance. The test focused on identifying the breakdown performance of marble and porcelain samples under dry and wet conditions.

Wettability. The condition of polymeric insulator surfaces can be crucially inferred from their wettability. Initially, these surfaces display hydrophobic traits, causing water to form distinct droplets. Over time, however, as the insulator ages, it loses this hydrophobicity. This degradation results in the

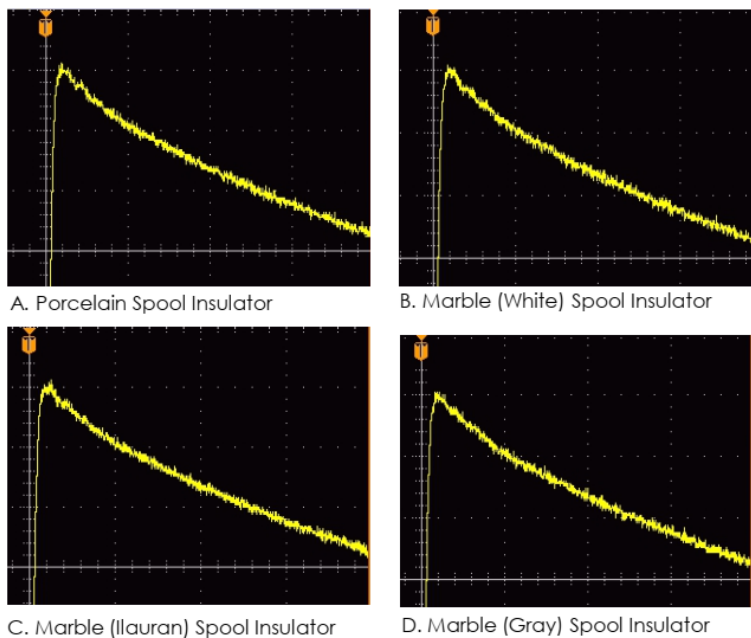


Fig. 3. Waveform results of the impulse flashover voltage test at 30 kV for porcelain (a) and marble spool insulators in White (b), Ilauran (c), and Gray (d).

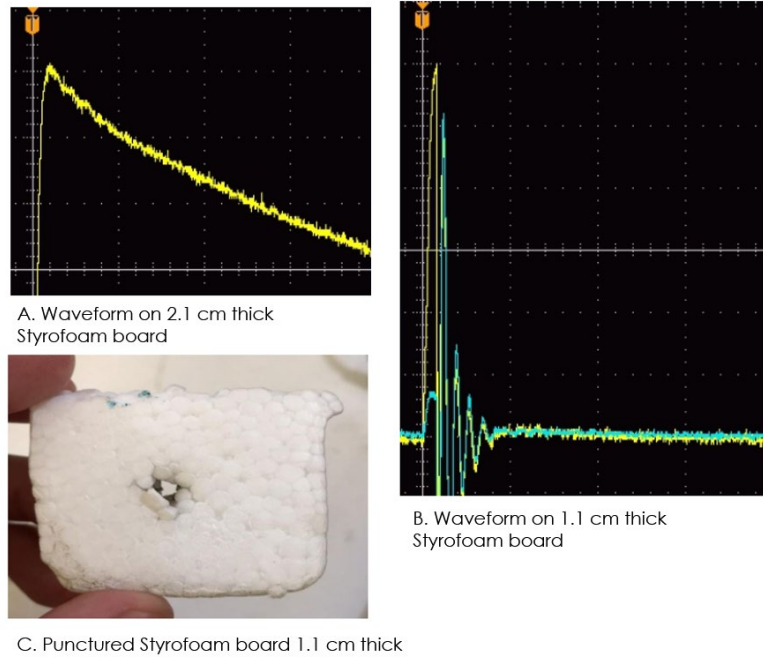


Fig. 4. A waveform generated on a 2.1 cm thick sample (a); on a 1.1 cm thick sample (b); and shows the punctured Styrofoam board 1.1 cm thick (c).

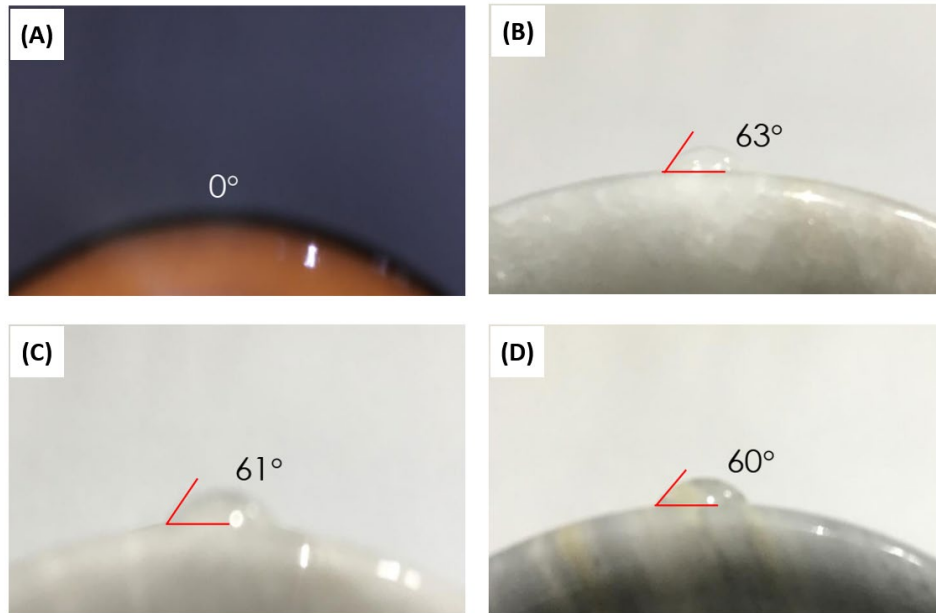


Fig. 5. Contact angles on porcelain (a); Ilauran white (b); white (c); and gray (d).

formation of continuous water films on the surface, which can lead to severe issues such as dry band arcing and flashovers, significantly impairing the insulator's long-term functionality (Chatterjee et al., 2020). The water resistance properties of marble and porcelain spool insulators were assessed using contact angle measurement. Cleaned sample surfaces were tested with water droplets under controlled conditions, and contact

angles were measured using macro photography and image analysis software.

The wettability of the marble and porcelain spool insulators was assessed using contact angle measurement. All samples were thoroughly cleaned with distilled water and dried before testing to remove any surface contaminants. A water droplet was carefully applied to each dry surface under ambient laboratory

Table 1. Summary of the abrasion test for marble and porcelain spool insulators.

Parameters	Marble	Porcelain
Weight of sample, g	5,080	5,151
Retained weight, g	3,695	3,496
Abrasion loss, %	27.28	32.13

conditions (~60% relative humidity). The droplet-surface interaction was recorded using a macro camera and analyzed using image processing software to determine the contact angle. This measurement quantifies the surface's hydrophobicity or hydrophilicity, helping assess its performance in real-world outdoor environments.

Abrasion Test. The abrasion testing method involved preparing samples of at least 5kg each from marble and porcelain spools (Tian et al., 2021). These samples were crushed to evaluate their durability and toughness. Subsequently, the destructive LA abrasion test was conducted, utilizing tumbler equipment containing standard steel balls. The powdered samples were placed inside the tumbler and mixed for 15 minutes at a specific speed and weight. Following the mixing process, only the remaining large chunks were retained. These retained chunks were then weighed to determine the amount lost due to abrasion. This method provides a direct and efficient means of assessing the abrasion resistance of marble and porcelain spools, which is crucial for evaluating their suitability for various applications.

RESULTS AND DISCUSSION

Marble Spool Insulators. As shown in Figure 2, each sample is distinguishable in terms of color and appears aesthetically appealing compared to existing porcelain or polymer spools on the market, which are typically brown, white, or black. This presents a local manufacturing advantage for Romblon, which is rich in marble resources and has established marble processing capabilities that can be extended to technical applications such as insulator production.

Impulse Flashover Voltage Test. The result of the 30 kV waveform generated by the lightning impulse equipment is shown in Figure 3.

The marble spool insulators developed passed the impulse voltage test, as there is no remarkable leakage voltage (no ripples on the waveform). This means that the marble material and design of the spool insulator were sufficient to resist the 30 kV impulse voltage without causing any visible damage to the samples. This result is similar to that of the porcelain spool insulator

tested. This performance is comparable to the findings of Zhang et al. (2018), who reported similar dielectric strength and flashover resistance in standard porcelain and glass insulators under lightning impulse conditions. The results demonstrate that locally sourced marble can achieve equivalent insulation capability, validating its potential as a functional alternative to conventional materials. Moreover, any voltage surge up to 30kW will not pass through the marble material. To confirm this, another test, such as the low-frequency flashover voltage test, is needed alongside the impulse flashover voltage test done in this study. To compare how the impulse flashover voltage test appears on a more porous insulating material, a separate test on a Styrofoam board at 2.1 cm and 1.1 cm thickness was done to compare as shown in Figure 4.

As observed in Figure 4c, the impulse lighting punctured the 1.1cm thick Styrofoam board, indicating that lighting can pass through a material as insulating like a Styrofoam board. Ripples on the generated waveform of voltage are observed on the punctured sample, as shown in Figure 4b, while no such ripple is monitored on a 2.1 cm thick sample, which was not punctured at all.

Wettability. The water contact angle on each sample is shown in Figure 5.

The result of the contact angle test shows that the water droplet's contact (θ) on the surface of the marble spool insulators is no less than 60° . For a material to be completely hydrophobic, it must have a contact angle greater than 90° . The porcelain spool's surface is completely hydrophilic on this test, while the marble spools are more hydrophobic. This finding aligns with Bi et al. (2020), who noted that composite insulators with moderate to high hydrophobicity often exhibit contact angles above 60° , indicating a favorable resistance to surface wetting. The marble samples, therefore, demonstrate surface characteristics similar to modern polymer-based hydrophobic insulators, suggesting their suitability for humid and outdoor conditions. This test relates not only to a material's electrical resistivity but to its behavior when in contact with liquids. The accumulation and adsorption of moisture on the material could reduce its insulating properties. Considering that the Philippines is a tropical

country, it is essential to determine how the marble spool insulator reacts to humidity and rain.

Abrasion Resistance. The result of the LA abrasion test is summarized in Table 1.

Data as shown above indicates that more material is crushed on the porcelain than on the marble, with a difference of 4.85%. This implies that marble is more durable and rigid than porcelain, making it a better alternative material for spool insulators.

CONCLUSION

In conclusion, this study demonstrates the feasibility of using marble as an alternative material for spool insulator fabrication. The fabricated marble spool insulators exhibit high electrical resistance up to 30 kV in both wet and dry conditions while showcasing superior hydrophobicity, durability, and rigidity compared to porcelain counterparts. These findings suggest that marble can offer performance characteristics that are equal to or better than traditional porcelain, particularly in terms of water repellency and abrasion resistance, two key factors for long-term outdoor use.

The positive market outlook, indicated by the increasing number of approved constructions, suggests significant potential for marble spool insulators, especially considering the demand from unregistered constructions. However, further testing, such as low-frequency flashover tests, is needed to validate the impulse flashover voltage results. Additionally, comprehensive market and feasibility studies are essential to accurately gauge the market potential of marble spool insulators in the Philippines.

ACKNOWLEDGMENT

The authors gratefully acknowledge the financial support provided by the Department of Science and Technology – Grants-in-Aid (DOST-GIA) Program through Romblon State University. This research would not have been possible without the funding assistance and institutional support extended to the project.

AUTHORS' CONTRIBUTIONS

M.L. Ical led the conceptualization, drafting of the initial manuscript, experimental analysis, and processing of results. J. Oliveros facilitated the research implementation, laboratory testing, and coordination of technical activities. J.G. Gacu contributed to the final manuscript preparation, critical review, and overall refinement of the paper. All authors read and approved the final version of the manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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