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Article

Assessing the potential of horsetail ash as a sustainable additive in infrastructure materials through ignition testing

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Abstract: This study assesses the application of horsetail ash as a sustainable soil stabilizer additive in infrastructure materials, highlighting the significance of environmentally friendly practices in construction. The horsetail plant (Equisetum Hyemale) which is recognized for its abundant silica content, was incinerated at different temperatures to produce ash for investigation. The study included initial analysis by visually inspecting and weighing samples, then conducting ignition tests to measure carbon content and evaluate pozzolanic properties. Subsequently, Energy Dispersive X-Ray Analysis (EDX) and Scanning Electron Microscopy (SEM) were used to examine the elemental composition and morphology of the ash. Ignition tests showed that higher incineration temperatures are associated with lower carbon content and a rise in crystalline silica forms. Incinerating at 700 °C effectively decreased carbon content while maintaining the amorphous silica structure, making it the ideal temperature for bulk incineration. The study shows that horsetail ash, particularly when processed correctly, has great potential as an eco-friendly and economical additive for improving soil characteristics in geotechnical uses.

Keywords: horsetail plant; ignition; infrastructure; additives; geotechnical engineering

1. Introduction

Sustainability in infrastructures (Gu, 2017; Regan, 2017) has driven innovative utilization of materials, especially in geotechnical engineering (Vieira, 2022). Horsetail ash is a notable sustainable material being considered for eco-friendly construction approaches. This sustainable byproduct, obtained from burning horsetail plants (Eken, 2023), signifies a significant shift towards more environmentally friendly options in infrastructure development (Guo et al., 2020), particularly in the field of ground improvement (Kamei et al, 2018) and stabilizing soil (Aamir et al., 2019; Adajar et al., 2020; Ubay et al., 2020; Ubay-Anongphouth and Alfaro, 2022).

Utilizing waste materials in geotechnical engineering is not merely a trend but an important step towards sustainability (Galupino et al., 2020; Rahman et al., 2022; Uy et al., 2021). The industry addresses important environmental issues like waste management and resource depletion (Zaman and Lehmann, 2011) by repurposing by-products like horsetail ash. This method minimizes the environmental effects of construction projects and supports the principles of a circular economy by converting waste into valuable resources (Blomsma, 2018). Incorporating sustainable waste into geotechnical engineering techniques demonstrates a commitment to reducing the environmental impact of infrastructure development (Amakye et al., 2021).

Recent studies on the utilization of sustainable materials in construction has emphasized the considerable capacity of agricultural byproducts such as rice husk ash (RHA) (Endale et al., 2023) and bamboo leaf ash (Onikeku et al., 2019) to improve the characteristics of concrete. Endale (2023) investigated the pozzolanic characteristics of RHA and found that using it as a partial substitute for cement can enhance the mechanical and durability properties of concrete. The enhancements consist of improved compressive, tensile, and flexural strength. Substituting materials in concrete not only improves its structural integrity but also promotes environmental sustainability by reducing the amount of cement used, thereby decreasing the associated carbon emissions (Zamora-Castro et al., 2021).

In addition, bamboo leaf ash has been recognized as a valuable pozzolanic substance (Villar Cociña et al., 2018). Experimental studies show that using it as a partial substitute for cement can improve the strength and longevity of concrete. The results indicate that incorporating both RHA and bamboo leaf ash into concrete mixtures can yield building materials that are more environmentally friendly, long-lasting, and economical (Maraveas, 2020).

Various methodologies have been developed to ensure the effective utilization of sustainable waste materials (Graettinger et al., 2005) such as horsetail ash in geotechnical projects. The ignition test is a crucial technique for evaluating the viability of a material. This test assesses the loss on ignition of materials to determine their composition and potential for improving soil properties (Bernal et al., 2017). By using these methods, engineers can confirm the effectiveness of horsetail ash and other sustainable waste materials, guaranteeing suitability for soil stabilization and ground improvement.

Using horsetail ash in infrastructure development, specifically for ground improvement, introduces new opportunities for sustainable construction methods. Its unique properties, such as its high silica content and pozzolanic activity (Hosseini Mohtasham and Gholizadeh, 2021), make it an excellent additive for soil stabilization projects. Engineers can enhance the durability and sustainability of infrastructure projects by improving the soil's load-bearing capacity through the incorporation of waste material (Anupam et al., 2013).

Horsetail ash, obtained from the horsetail plant (*Equisetum hyemale*), presents a promising eco-friendly material for construction, especially advantageous in developing nations with notable economic and environmental limitations (Mihajlovski et al., 2021). The horsetail plant flourishes in diverse climates and is frequently encountered in damp, sandy, or marshy soils, which are widespread in numerous regions worldwide, including Asia, Europe, and North America (Contreras and Ramirez, 2022). The extensive accessibility of this resource makes it a practical option in many developing areas where it is crucial to reduce costs and support local economies by sourcing and using construction materials locally (He et al., 2018).

The cost-effectiveness of construction materials is of utmost importance in developing nations. Horsetail ash, derived from locally abundant and easily accessible horsetail plants, offers a substantial decrease in material expenses (Masłowski et al., 2020). The conversion of horsetail to ash can be accomplished through uncomplicated and inexpensive methods, such as drying (Rodrigues-Das-Dores et al., 2020) and controlled burning (Schneider et al., 2020). These techniques can be readily applied in community settings without the requirement for advanced technology or substantial financial resources.

Horsetail ash has been selected for geotechnical purposes due to its environmental benefits and functional advantages. This sustainable waste material provides a solution for agricultural waste disposal and helps reduce greenhouse gas emissions associated to conventional construction materials (Olaiya et al., 2023). The geotechnical engineering field proactively addresses global sustainability challenges by prioritizing the use of eco-friendly alternatives (Rahman et al., 2022) such as horse tail ash. From an economic standpoint, utilizing horsetail ash in infrastructure projects offers a cost-effective option compared to conventional building materials. Being a by-product of agricultural processes, its availability reduces material costs and boosts local economies by encouraging the use of locally sourced materials (Turan et al., 2022).

Utilizing horsetail ash and other sustainable wastes necessitates an extensive understanding of their characteristics and effects. By conducting thorough testing and analysis, like the ignition test, the geotechnical engineering field can establish a robust knowledge to enhance the effective use of these materials. Thus, this study aims to assess the potential of horsetail ash as a sustainable additive in infrastructure materials through ignition testing.

2. Materials and methods

2.1. Material

The horsetail plant used in the study is *Equisetum Hyemale* or rough horsetail since it is readily available and research regarding its silica composition is known (Hosseini Mohtasham and Gholizadeh, 2021). The plant, shown in **Figure 1**, are locally grown in the Philippines.

Figure 1. Horsetail plants used in the study.

The preparation of horsetail ash follows a systematic procedure comprising three main stages: the boiling process (Guevara-Lora et al., 2022), the drying process (Rodrigues-Das-Dores et al., 2020), and the incineration process (Schneider et al., 2020). Research on the physical and chemical makeup of the plant reveals that horsetail accumulates significant quantities of silica, extending from its rhizome to its leaves (Law and Exley, 2011). This extensive silica deposition is a key factor influencing the properties and effectiveness of the resulting ash.

2.2. Methods

2.2.1. Preparation of horsetail plant

Horsetail plants are first boiled to eliminate toxins, particularly the anti-nutrient thiaminase. Boiling is necessary due to the plant's composition containing harmful substances when consumed raw. According to a study by Moerman (1998), boiling the horsetail plant for 5 min to eliminate any adhering soil, microorganisms, or other impurities that may compromise the quality of ash or disrupt the incineration procedure.

After boiling, the essential next step is to dry the plants in the sun. This stage is designed to eliminate any remaining moisture from the plants to prepare them for incineration. The drying process is carried out until the plant stems reach a light brown color and become brittle, signifying their readiness for the next process, shown in **Figure 2**. To optimize furnace capacity and aid in the incineration process, the dried stems are cut into pieces no longer than 1 inch. This step is essential for optimizing ash generation.

Figure 2. Dried horsetail plants used in the study.

2.2.2. Incineration

The horsetail plants were incinerated using an electric furnace. This furnace can reach and sustain controlled temperatures up to 1100 °C, which is crucial for the requirements of incineration processes and ignition tests. The setup features an advanced ventilation system that is specifically designed to protect the sample from direct exposure to flames and other particles, thus guaranteeing the experiment's integrity.

The incineration methodology is based on the process outlined by Behak (2017) for extracting silica from rice husks. The comparison is made because both materials contain amorphous silica that is organically integrated into the structures of the plants.

The electric furnace utilized in the experiment had internal dimensions of 35.5 × 12 × 18 cm, allowing for a crucible with a 14 cm diameter. The horsetail plants were cut into small pieces before being burned to ensure they would fit the furnace and crucible sizes. The experiment investigated the effects of four different temperatures (350 °C, 550 °C, 700 °C, and 900 °C) for one hour each to find the optimum conditions for generating low carbon ash while maintaining the integrity of amorphous silica (Behak, 2017). The study found that keeping the temperature within the range of 550 °C to 700 °C was optimal, but it could be expanded from 350 °C to 900 °C to avoid the production of quartz and other undesirable compounds.

Twelve (12) samples were prepared for each temperature setting in the experimental setup. Some samples were designated for analysis using EDX and SEM, while the rest were used for ignition tests. Larger quantities of horsetail plants were processed at the optimal incineration temperature using larger crucibles to handle the increased volume.

The procedure started by activating the furnace and ventilation system to prevent gas leakage, then preheating to the desired temperatures. The horsetail plants were readied and placed in crucibles that could endure temperatures of up to 1000 °C during this stage. After the furnace reached the desired temperature, the samples were promptly placed into the furnace using tongs to reduce smoke production. After being incinerated for an hour, the samples were removed and left to cool for 30 min to prevent containers from melting due to the ash's heat.

2.2.3. Ignition test

Ignition tests were conducted using smaller crucibles compared to those used for bulk incineration to assess the incineration efficiency of horsetail plants. Four 50 mL crucibles were utilized for each temperature trial in the tests, with the samples combined for an overall evaluation. The color of the ash after incineration was used as an initial indication of how well carbon had been eliminated during the process. An examination of the ash color was performed to estimate the silica content and remaining carbon, based on the methodology of Behak (2017). This step is important because it offers an initial qualitative evaluation of the incineration process, where variations in ash color indicate the effectiveness of the carbon burn-off.

An ash color with a white hue was found to be a sign of high residual carbon content, indicating inadequate incineration. The observation was conducted simultaneously with the ignition tests to enable a comparative analysis of the data collected. The ignition test, used to measure the carbon lost during combustion, gained significance because of the convenience provided by the electric furnace. The test requires a precise process of weighing the ash sample both before and after exposing it to elevated temperatures, with the change in weight indicating the loss of carbon.

The experiment was set up to conduct two trials at each temperature setting using the ability of the furnace to hold four crucibles at once, enabling simultaneous processing of samples at various temperature ranges.

The preparation for the ignition test required accurate measurements, where the crucibles were weighed with a digital balance to an accuracy of 0.00001 g. Each crucible contained one gram of horsetail ash obtained from different temperature intervals during the incineration procedure. The prepared crucibles were placed in a cold furnace without preheating to establish a uniform starting condition for all samples. The crucibles were placed, and then the electric furnace and its ventilation system were turned on to start the ignition test.

The heating procedure for the ignition test was carefully structured, gradually increasing the temperature to 500 °C within one hour. After reaching and sustaining the initial temperature for an hour, it was raised to 750 °C and maintained for another hour to guarantee complete combustion. The progressive heating process was created to replicate the conditions required for efficient carbon burn-off, offering a controlled setting for the ignition test.

After the heating stages were finished, the samples were left to cool for 30 min before being weighed once more. The weight change before and after heating was used to calculate the ignition loss percentage. By conducting two trials and analyzing data using EDX and SEM, the optimal temperature range for bulk incineration was determined.

2.2.4. Elemental analysis and morphology

Energy Dispersive X-Ray Analysis (EDX) and Scanning Electron Microscopy (SEM) were used to study the chemical composition and morphology (Fakhari et al., 2019) of the ash. The analyses were performed on the ash in its original state after incineration, without any modifications such as grinding for testing, as shown in **Figure 3**. It was crucial to prepare small and thin samples due to the diverse incineration temperatures of the horsetail plant. Eight samples were thoroughly analyzed using both EDX and SEM to reveal the detailed composition of the ash.

The EDX analysis was conducted on a specific sample that was small and thin, reflecting the condition of the ash after incineration, where the structure of the plant was mostly preserved. The specimen was placed into a scanning transmission electron microscope (STEM) with an electron diffraction system, which operated in a vacuum to avoid air particle interference. The EDX process entails aiming an electron beam at the sample, which interacts with the atoms of the sample based on the atomic structure, leading to electron scattering or diffraction. The scattering pattern reveals the crystal lattice structure, orientation, and parameters of the material, which are analyzed with specialized software to extract detailed compositional information.

Figure 3. Unground horsetail plants used in the study.

The SEM analysis began by applying a thin gold coating to the sample to improve electron conductivity. The sample was then placed on a container specifically made for the SEM chamber. The SEM chamber was evacuated to create a vacuum environment to enhance the interaction of the electron beam with the sample. In SEM, the focused electron beam interacts with the atoms of the materials, producing signals that are amplified and processed to create high-resolution images of the sample’s surface, like the EDX process. The images display the texture, morphology, and distribution of silica in the ash.

EDX and SEM tests provide complementary insights into the composition of the ash by focusing on electron-material interactions. EDX offers quantitative elemental composition data, while SEM provides detailed surface morphology images (Fakhari et al., 2019). These methods provide a detailed overview of the ash, showing not only the silica content but also the structural features that may impact its possible uses.

3. Results and discussions

3.1. Horsetail ash

The initial procedure in evaluating the horsetail ash included measuring its weight and visually inspecting it, with a particular focus on the color of the ash. This aspect is essential because it offers information about the shape of silica and the amount of carbon present in the ash. **Table 1** aids in linking ash color to the specific type of silica present: pink ash indicates tridymite and cristobalite, white and grey suggest quartz, and black and grey signify amorphous silica. **Table 2** shows the relationship between ash color and carbon content, where black ash has high carbon, grey ash has low carbon, and white and pink ash have no carbon content. These categories, derived from the research of Behak (2017) on soil stabilization using rice husk ash, help in anticipating the composition of the ash and its ability to undergo pozzolanic reactions, which depend on these factors.

Table 1. Silica composition in terms of ash color (Behak, 2017).

Color of the Ash	Form of Silica
Pink	Tridymite, Cristobalite
White and Grey	Quartz
Black and Grey	Amorphous

Table 2. Carbon content in terms of ash color (Behak, 2017).

Color of the Ash	Carbon Content
Black	High Carbon
Grey	Low Carbon
White and Pink	No Carbon

Amorphous silica, with its greater surface area, is more reactive and thus more favorable for pozzolanic reactions than crystalline silica. Carbon presence can negatively impact the reactivity of silica with calcium ions from lime, resulting in a less effective pozzolanic reaction. The initial visual observations established which temperatures are expected to produce the lowest carbon content and the highest amount of amorphous silica, leading to a more robust pozzolanic reaction. **Figure 4** illustrates the outcomes of the incineration experiments, providing a comparison of the two sample trials.

Figure 4. Horsetail ash samples by temperature.

Each sample of horsetail plants underwent incineration for one hour. **Figure 4** illustrates the results, with the bottom row showing the first trial and the top row showing the second trial. The ash samples are organized in ascending order of incineration temperatures, from 350 °C on the left to 900 °C on the right. The observations indicated that ash color shifted from black-grey at lower temperatures to progressively whiter shades as the temperature increased, notably at 550 °C.

The samples incinerated at 700 °C exhibit a noticeable change as they appear grey, suggesting a transformation of the silica into a crystalline structure. At 900 °C, the ash was white, indicating thorough carbon combustion and a potential prevalence of quartz-like silica over amorphous silica. The ash at 350 °C, although darker, exhibits similarities with the 550 °C samples, suggesting a notable carbon presence resulting from incomplete combustion.

The variations in ash color, particularly between 550 °C and 700 °C, indicate a change in silica structure and carbon content. Visual inspection can help form hypotheses, but it is difficult to determine the precise composition without additional analysis. However, the discoloration suggests that the ideal incineration temperature for producing the desired ash quality, which promotes the creation of amorphous silica and complete carbon burn-off, probably lies between these two temperature thresholds.

3.2. Ignition test

The ignition test compares ash samples collected at various temperatures by measuring weight loss after re-ignition, indicating the amount of carbon burned off. A greater weight loss indicates a higher initial carbon content in the sample prior to testing. The data in **Table 3** shows that weight loss after ignition decreases as temperature increases, suggesting a lower carbon content in the samples at higher incineration temperatures.

Table 3. Weight difference after ignition.

Temperature	**Difference in Weight after Ignition (g)**		
	Trial 1	**Trial 2**	**Trial 3**
350 °C	0.5740	0.5522	0.5259
550 °C	0.1624	0.1913	0.1633
700 °C	0.1109	0.0985	0.0942
900 °C	0.0287	0.0250	0.0236

The results show that weight loss decreases as incineration temperature increases, with the most significant decrease occurring at temperatures above 550 °C. These results are consistent with the hypothesis that increased temperatures lead to more complete combustion and, therefore, less carbon residue in the ash. The data clearly indicates that 900 °C is the temperature at which the ash experiences the least weight loss upon re-ignition, implying that it is the temperature where the least amount of carbon remains in the ash. This temperature may be considered ideal for bulk incineration if minimizing weight loss is the main priority.

The significant decrease in weight loss becomes apparent at temperatures of 550 °C and above. Ash exposed to temperatures of 550 °C and higher experiences a noticeable reduction in weight, signaling a substantial loss of carbon. This data is important because it indicates that incineration at 550 °C significantly decreases the carbon content, potentially impacting the efficiency and feasibility of the incineration procedure.

Selecting the ideal temperature for bulk incineration involves finding a balance between efficiency and safety. Incinerating at 550 °C burns off a substantial amount of carbon, while 900 °C leads to the least weight loss, suggesting minimal carbon content. The potentially suitable temperature for bulk burning is 550 °C, considering factors like incineration duration and sample stability. At 550 °C, the reduced risk of immediate combustion minimizes sample instability, potentially resulting in more consistent and controlled results.

The ignition test data indicate that a temperature of 550 °C maintains an efficient balance by successfully burning most carbon residue without the drawbacks associated with higher temperatures. This temperature enables effective carbon removal while reducing the chances of rapid combustion, making it a potentially optimal option for large-scale incineration.

3.3. Elemental analysis and morphology

The initial assessment of the horsetail ash composition commenced with a fundamental examination of weight and color. The initial observations were improved by using advanced techniques like Energy Dispersive X-Ray Analysis (EDX) to analyze the elemental composition of the ash and Scanning Electron Microscopy (SEM) to study its morphology. These techniques necessitate the samples to be covered with gold, which, although essential for the experiments, does not impact the final results.

The EDX and SEM analyses focused solely on the surface of the samples, providing results that accurately represented the exterior of the undisturbed sample.

Tables 4–7 exhibit the atomic concentration of elements in the sample, focusing on Gold, Carbon, Oxygen, and Silicon, which are the four most abundant elements found. Silicon is the most abundant element, especially in terms of weight. The reduction in carbon content is directly related to the incineration temperature. Samples incinerated at 350 °C had the highest carbon content, whereas those incinerated above 700 °C had no carbon on their surface.

Table 4. Horsetail burned at 350 °C.

Element	Sample 1			Sample 2			Sample 3		
	Atomic Conc.	Weight	Order	Atomic Conc.	Weight	Order	Atomic Conc.	Weight	Order
Carbon	31.42	3.04	1	12.81	1.07	1	14.42	1.23	1
Oxygen	5.62	0.72	2	10.01	1.11	2	9.44	1.07	2
Silicon	0.20	0.05	3	4.01	0.78	3	3.45	0.69	3

Table 5. Horsetail burned at 550 °C.

Element	Sample 1			Sample 2			Sample 3		
	Atomic Conc.	Weight	Order	Atomic Conc.	Weight	Order	Atomic Conc.	Weight	Order
Carbon	-	-		-	-		-	-	
Oxygen	17.78	1.94	1	10.69	1.04	1	19.10	2.13	1
Silicon	4.57	0.88	2	3.39	0.58	2	6.46	1.27	2

Table 6. Horsetail burned at 700 °C.

Element	Sample 1			Sample 2			Sample 3		
	Atomic Conc.	Weight	Order	Atomic Conc.	Weight	Order	Atomic Conc.	Weight	Order
Carbon	5.26	0.49	3	5.57	0.57	2	4.96	0.47	3
Oxygen	18.21	2.25	1	22.06	3.01	1	19.27	2.44	1
Silicon	5.56	1.20	2	4.97	1.19	3	5.27	1.17	2

Table 7. Horsetail burned at 900 °C.

Element	Sample 1			Sample 2			Sample 3		
	Atomic Conc.	Weight	Order	Atomic Conc.	Weight	Order	Atomic Conc.	Weight	Order
Carbon	-	-		-	-		-	-	
Oxygen	17.53	1.89	1	2.73	0.24	1	21.62	2.61	1
Silicon	6.91	1.31	2	1.82	0.28	2	4.00	0.85	3

Scanning electron microscopy (SEM) offered a detailed examination of the microstructure of the sample. **Figures 5** and **6** show the plant structure that was preserved after incineration, indicating that the samples had not undergone any modifications prior to analysis. The SEM images show the surface of the stem, which is the main component of the sample. **Figure 7** provides a detailed illustration.

of the epidermal layer of the plant, showing silicified scales and structures like sunken stomata enclosed by silicified papillae, which are distinctive characteristics found on the surface of the stem.

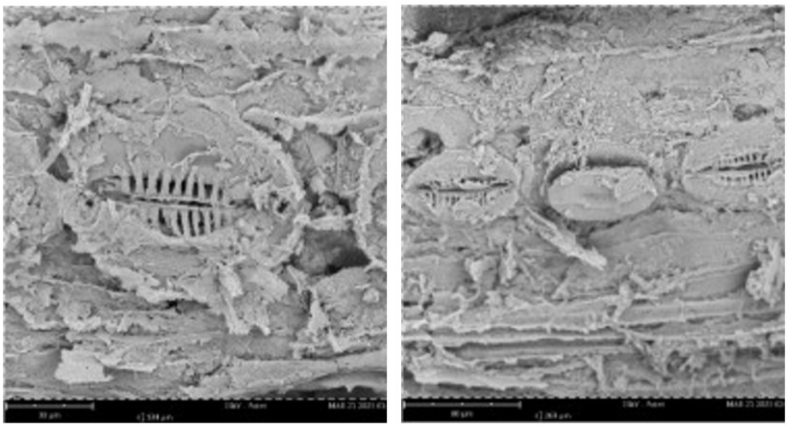

Figure 5. Adult stomata with radiating ribs and neighboring epidermal cells.

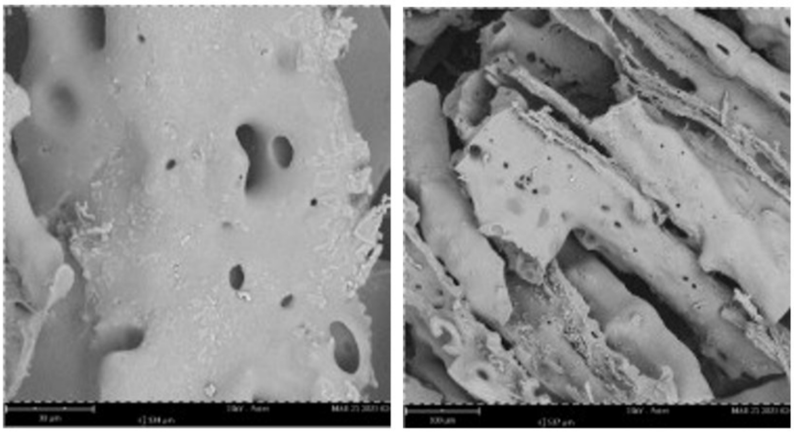

Figure 6. Partially covered stomatal pores.

SEM images of samples incinerated at 550 °C and higher show preserved plant structures, specifically the detailed ribs forming the silicified elements mentioned in the research of Guerriero et al. (2020). Samples burned at 350 °C, as shown in **Figure 7**, retain most of their plant structure without exposed rib structures, suggesting an incomplete combustion process supported by ignition test and EDX results. The smooth surface of the figure indicates that the epidermal cells and the rib-like structures underneath have not been affected or changed by the burning process.

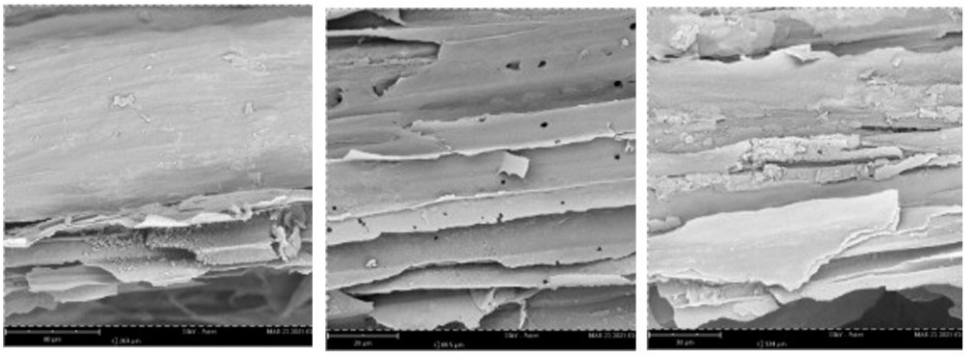

Figure 7. Horsetail plant stem epidermal layer (Horsetail Burned at 350 °C).

At 900 °C, shown in **Figure 8**, the ash shows a notable change: parts of the stem's epidermal layer are absent, as indicated by the lack of stomatal scales seen in the 700 °C samples. It suggests that either the sample was damaged after incineration or that the high temperature caused the plant's structure to break down, making it difficult to identify any remaining plant structure in the ash.

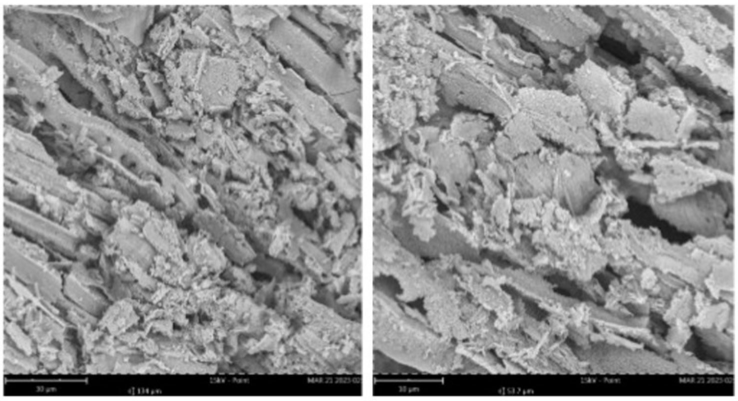

Figure 8. Horsetail plant stem epidermal layer (Horsetail Burned at 900 °C).

The experimental results offer an extensive understanding of the ash composition at different temperatures. Horsetail ash incinerated at temperatures of 550 °C and higher experiences significant carbon removal, with the most effective results seen at 700 °C. The temperature reached a state of equilibrium, demonstrated by the low carbon content from EDX analyses and minimal weight loss from the ignition test, while maintaining a high concentration of amorphous silica, as shown by the distinct silicified plant structures that are still present. The weight loss seen during the ignition test is not connected to silica loss, indicating that the structural integrity of silica remains intact even at high incineration temperatures.

The optimal temperature for incinerating horsetail plants in large quantities is 700 °C, based on the findings. This temperature is effective for reducing carbon content and preserving the amorphous silica structure, crucial for the pozzolanic reactivity of the ash.

4. Conclusion

The comprehensive study evaluating the viability of horsetail ash as a sustainable additive in infrastructure materials using ignition testing has produced significant results. The research aimed to provide a sustainable and cost-effective alternative to traditional soil stabilizers by investigating the use of this waste material in geotechnical engineering. The investigation involved thorough preparation, burning, and examination of the horsetail plant to analyze the physical and chemical properties of the ash produced.

The ignition tests were crucial for assessing the composition of the ash, particularly its carbon content and silica form. The study showed that incineration temperatures have a significant impact on carbon content, with higher temperatures resulting in greater carbon removal and a possible transition to the crystalline form of silica. The findings were essential for identifying the ideal temperature range to produce ash with the desired properties for utilization as a pozzolanic material in infrastructure projects.

The Energy Dispersive X-Ray Analysis (EDX) and Scanning Electron Microscopy (SEM) offered a more thorough understanding of the elemental composition and morphology of the ash. The scanning electron microscope images provided a comprehensive look at the well-preserved plant structures, such as the silicified scales and papillae, which suggest the ability of the ash to improve soil characteristics.

The ash incinerated at 700 °C showed the most effective combination of decreased carbon content and maintained amorphous silica structure. This temperature was determined to be the most appropriate for bulk incineration, considering both the effectiveness of the ash as a pozzolanic material and the efficiency of the incineration process. The reduced carbon content at this temperature, along with the existence of amorphous silica, indicates that the ash could be a valuable material for stabilizing soil and improving the durability of infrastructure materials.

The findings of this study make a substantial contribution to sustainable construction by offering a scientifically proven method for converting agricultural waste into useful construction material. Moreover, using horsetail ash is a cost-effective choice for developing nations, especially in areas where the horsetail plant is abundant. This study advocates for the utilization of an easily accessible agricultural by-product as a sustainable construction material, aiming to boost local economies and encourage the integration of eco-friendly technologies in the construction sector.

The findings are expected to promote more investigation in geotechnical engineering and broader use of sustainable materials, such as horsetail ash, in infrastructure development, supporting a more environmentally friendly and sustainable future.

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