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Review Article

A Review of Chemical and Physical Properties of Wood Waste Ash and its Cement Blended Concrete

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Abstract — The study investigates the chemical composition and physical properties of wood waste ash as a partial substitute for cement in concrete and as a raw material in cement manufacturing. Wood waste ash contains silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3), and quicklime (CaO) which makes it suitable for use in the above-mentioned applications. The blending of wood waste ash and ordinary Portland cement (OPC) at various levels of cement replacement produces a new type of blended cement having physical properties and heat kinetic properties in comparison to neat OPC. Wood waste ash/OPC blended cement has better properties such as standard consistency setting times, soundness, heat evolution characteristics, and the microstructure of hardened cement paste compared to OPC. However, factors including heat treatment temperature, species of trees from which the wood wastes were derived, types of combustion technology, and the thermodynamics of the furnace affect wood ash qualitatively and quantitatively during the incineration process of raw wood waste. These issues can be addressed by characterizing the ash before being used as constituent material in concrete and blended cement paste production.

Keywords — Wood Waste Ash; Blended cement; Ordinary Portland Cement; Pozzolan; Partial cement replacement; Environmental threat.

1. Introduction

As the world's population grows and urbanizes, the demand for cement and wood has skyrocketed. Unfortunately, wood is often used as fuel in industries that burn it to generate electricity, resulting in a surplus of wood ash (WA) that poses a serious environmental threat to livestock [1]. While most wood ash is disposed of in landfills, this method can be problematic due to the fine particulate matter that can easily become airborne and cause respiratory issues for nearby residents [2], [3]. Groundwater contamination is also a concern due to the leaching of heavy metals in the ash or seepage of rain in water [4]–[6]. The current landfill approach is both costly and unsustainable, especially in third-world countries like Nigeria where poverty is widespread. A more cost-effective solution is needed to address this issue.

As earlier mentioned, the construction industry is experiencing significant growth as a result of an increase in the human population and the transformation of more rural areas into cities. This development has led to a significant increase in the demand for cement, which is a vital material in the production of concrete. Unfortunately, the process of cement production requires the use of limestone and energy, resulting in the release of large amounts of carbon dioxide (CO2) into the atmosphere. This increased demand for cement can lead to environmental degradation[7]–[9] due to limestone extraction activities, increased use of fossil fuels, and higher greenhouse gas emissions. One potential solution to this problem is to reduce CO_2 emissions during cement manufacturing by replacing cement with locally available by-products that are pozzolanic. Ashes from various sources, including industries and agriculture, are often considered waste but can be used as an effective mineral admixture of pozzolan to cement at various percentages. Rice husk ash and fly ash are two of the major ashes that have been proven to be effective [10], [11].

Several research reports [4], [12], [13] have explored the possibility of utilizing wood ash as a replacement material for the energy-intensive hydraulic fracture process in concrete production. The findings suggest that wood ash possesses the necessary properties to be used as a partial replacement for cement in the creation of structural-grade concrete. This method can result in concrete with satisfactory mechanical and durability characteristics. Marthong [14] proposes that the optimal ratio for sawdust ash admixture cement is 10% wood ash to cement. Studying wood ash provides a potential solution to the waste management issue of wood waste ash and can help decrease the use of energy-intensive hydraulic cement production in favor of more eco-friendly concrete materials. Analyzing the incorporation of wood ash as a cement replacement material in blended cement and concrete can address environmental challenges and reduce production costs.

2. Related Work

Raheem and Ige [15] researched the chemical composition and physical characteristics of sawdust ash blended cement. They found that a 15% substitution level of cement with sawdust ash was optimal for achieving the desired engineering properties. Chowdhury et al. [16] investigated concrete strength development with wood ash blended cement and used soft computing models to predict strength parameters. They concluded that wood ash could be blended with cement without adversely affecting the strength properties of the concrete. Raheem et al. [17] looked at the physical and chemical properties of sawdust ash, as well as the workability and compressive strength properties of concrete produced by replacing different percentages, ranging from 5% to 25%, of ordinary Portland cement with wood sawdust ash. They concluded that a 5% substitution of sawdust ash was sufficient to achieve maximum strength gain. Batool et al. [18] studied the effectiveness of wood waste sawdust to produce medium-to-low-strength concrete materials. They investigated the application of sawdust as fine aggregate and its impact on the properties of hardened concrete. They found that the addition of sawdust reduced workability and had an adverse effect on other concrete properties as the replacement level increased. However, immersing the concrete in sulphate for 28 days improved its strength. Chowdhury et al. [19] reviewed the use of wood waste ash as a partial cement replacement material for making structural-grade concrete. They concluded that the quality and quantity of wood ash vary depending on factors such as combustion temperature and wood species. Meko and Ighalo [20] investigated the use of Cordia Africana wood sawdust ash as a partial cement replacement in C25 concrete. They found that sawdust ash (SDA) can be used successfully as a cement replacement in C25 concrete up to 5% replacement, resulting in a 2.19% reduction in the use of virgin material. Ikponmwosa et al. [21] conducted an experimental and numerical investigation into the effect of sawdust ash on the performance of concrete. They found that SDA can be classified as class C pozzolan due to a combined percentage of 74.31% of SiO_2, Al_2O_3, and Fe_2O_3. However, the incorporation of SDA affected the properties of the produced concrete. Onyeka [22] researched the use of industrial waste, particularly sawdust ash, in the production of self-compacting concrete. They recommended a 5% and 10% ash replacement for casting slabs, beams, and columns due to their strength and surface texture. Orogbade and Raheem [23] investigated the chemical and physical characteristics of blended cement produced from softwood ash. They found that Anacardium-Occidentale ash (AOA) was suitable for use as a pozzolan and that the AOA blended cement satisfied standard requirements for up to a 20% replacement level. Gopal et al. [24] studied concrete strength with wood ash blended cement. They found that compressive strength, split tensile strength, and flexural strength parameters increased at 4% partial replacement but decreased with increasing wood ash replacement.

3. Wood Ash (WA) Concrete and Pozzolan

Wood ash is a finely powdered substance that remains after the burning of wood, whether in a residential fireplace or an industrial power plant. For many years, gardeners have utilized it as a valuable source of potash. The amount and chemical makeup of the ash can vary depending on a variety of factors, such as the type of wood used, the temperature at which it was burned, and the length of the combustion process.

The use of wood ash as a pozzolana in construction has been researched extensively. Pozzolanas are materials that do not have cementitious properties on their own, but when mixed with water and calcium hydroxide, they can react to form compounds with similar properties to cement [25]. Wood ash, a byproduct of burning wood, is similar to fly ash in that it contains various elements such as carbon, calcium, potassium, magnesium, phosphorus, and sodium. The composition of wood ash includes SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, TiO_2, K_2O, and SO_3, with LOI, moisture content, and available alkalis ranging from 0.1% to 33%, 0.1% to 22%, and 0.4% to 20%, respectively. Interestingly, almost all the compounds found in wood ash are also present in fly ash [26].

To qualify as a pozzolan, a substance must contain key oxide compounds such as silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3), and quicklime (CaO). ASTM C618 [25], states that for biomass fly ash or any other finely divided powder to be suitable as a pozzolan, it must have substantial amounts of silica and alumina compounds. Wood ash typically contains varying levels of CaO, ranging from 4% to 70%, which makes it a promising candidate for use in the cement industry. Ash with lower CaO content and a notable amount of SiO2 can be utilized to replace cement, while ash with higher CaO can be utilized as a raw material during cement production [27].

Concrete is a versatile building material composed of several key components, including Portland cement, water, and aggregate [28]–[32]. Aggregate is a critical ingredient in concrete and can be either natural, such as sand or gravel, or artificial, like steel shot or broken brick. The binder in concrete is also essential, as it holds the aggregate particles together to form a strong, durable material. Cement hydration, resulting from the reaction between cement and water, is the most commonly used binder. In addition, admixtures, sometimes referred to as pozzolan, can be added to concrete mixes to modify certain properties.

3.1 Physical Properties of Wood Ash

Wood ash is composed of a mixture of particles in varying sizes that are typically sharp and angular [33]., resulting from either partially burned or unburned wood or bark. About 50% of wood ash passes through sieve #200 (75 μM), while 31% is retained on sieve #32 (45 μM) in terms of fineness. The degree of variation in wood ash fineness is significant, with amounts retained on a 45 μM sieve ranging from 23% to 90%.

When produced at 1000 oC, wood waste ash is characterized by two primary phases: a fiber-like continuous layer and particle-like aggregates. The former is highly aqueous and has a high carbon content, while the latter is mostly composed of silica and alumina compounds with low carbon content, as indicated by energy-dispersive X-ray (EDX) results. These findings can be corroborated by examining various wood ash images, particularly residual ash from the incineration of wood waste ash.

3.2 Chemical Properties of Wood Ash

The ash resulting from burning wood at an uncontrolled temperature is highly alkaline, with a pH value between 9.5 and 10.1 [34]. It contains a significant amount of volatile matter, ranging from 4.63% to 8.40%, expressed as mass loss upon ignition at a burning temperature of 750 ± 50°C [4], [12].

Through X-ray diffraction (XRD) analysis, researchers have determined that the main phases of the chemical compound within the ash are silica and calcium carbonates [12]. However, some have also detected the presence of additional phases, including portlandite [Ca(OH)2] and lime (CaO) [2].
Further X-ray Fluorescence (XRF) analysis has shown that the ash contains a significant amount of silica [34]–[36]. The total chemical composition of pozzolanic essential compounds, including silica, alumina, and ferric, was found to range from 62.14% to 80.67%, with a mean value of 72.8%, similar to those of class N and F coal fly ashes. The examined wood ash sample had a wider range of total chemical composition of silica, alumina, and ferric compounds, ranging from 18.6% to 59.3%.

Various researchers, including [34], have discovered that wood waste ash is highly reactive chemically. The Pozzolanic Activity Index (PAI) of wood waste ash is 75.9%, exceeding the minimum ASTM C618 requirement of 70%. This indicates that wood waste ash is a viable pozzolan. It is worth noting that wood waste fly ash with a higher chemical composition of SiO_2 + Al_2O_3+ Fe_2O_3 exhibits greater pozzolanic reactivity than wood waste fly ash with a lower SiO_2 + Al_2O_3+ Fe_2O_3 chemical composition. This demonstrates a strong correlation between wood waste fly ash pozzolanicity and its total chemical content of SiO_2, Al_2O_3, and Fe_2O_3.

Additionally, elemental analysis of wood waste fly ash samples revealed the presence of Ca, Si, Al, and Mg elements on the surface of the particles, which is comparable to the presence of these elements on the surface of cement particles. Table 1 shows the chemical composition of wood waste fly ash obtained by Rajamma et al. [37].

Table 1: Chemical Composition of Wood Waste Fly Ash.

Element	Class F Fly Ash (Wt. %)	Class C Fly Ash (Wt. %)
SiO_2	41.0	28.0
Al_2O_3	9.3	6.2
Fe_2O_3	2.6	2.2
CaO	11.4	25.4
MgO	2.3	5.0
Na_2O	0.9	3.3
K_2O	3.9	3.2
TiO_2	0.4	0.3
MnO	0.3	0.7
P_2O_5	0.9	0.9
Cd	1.0mg/kg	1.3mg/kg
Pb	191mg/kg	12mg/kg
Cu	99mg/kg	27mg/kg
Cr	47mg/kg	73mg/kg
Hg	< 1mg/kg	< 1mg/kg
Ni	35mg/kg	27mg/kg
Zn	376mg/kg	34mg/kg

Source: Rajamma *et al*. [37].

Table 2 displays the chemical composition of wood waste ash, as reported by a range of researchers. Their findings indicate that the leachate of wood waste ash contains elevated levels of metallic ions, including arsenic, chromium, iron, and zinc.

Table 2: Analysis of elemental analysis of Wood Waste Ash Obtained Different Researches

Chemical compound	Elinwa and Ejeh (2004)	Nail *et al* (2003)					Abdullahi (2006)
		W_1	W_2	W_3	W_4	W_5	
SiO_2	67.20	32.40	13.00	50.70	30.00	8.10	31.80
Al_2O_3	4.09	17.10	7.80	8.20	12.30	7.50	28.00
Fe_2O_3	2.26	9.80	2.60	2.10	14.20	3.00	2.34
CaO	9.90	3.50	13.70	19.60	2.20	25.30	10.53
MgO	5.80	0.70	2.60	6.50	0.70	4.50	9.32
TiO_2	---	0.70	0.50	1.20	0.90	0.30	---
K_2O	---	1.10	0.40	2.80	2.00	2.70	10.38
Na_2O	0.08	0.90	0.60	2.10	0.50	3.30	6.50
SO_3	0.45	2.20	0.90	0.10	2.10	12.50	---
C	---	---	---	---	---	---	---
P_2O_5	0.48	---	---	---	---	---	---
LOI (%)	4.67	31.60	58.10	6.70	35.30	32.80	27.00

Source: Udoeyo *et al*. [4].

3.3 Properties of Wood Waste Ash Blended Cement

By incorporating wood waste ash into ordinary Portland cement (OPC) at varying levels of cement replacement, a novel blended cement can be produced that exhibits unique physical and heat kinetic properties not found in pure OPC. Research indicates that the properties of wood waste ash/OPC blended cement differ significantly from those of OPC, including standard consistency setting times, soundness, heat evolution characteristics, and the microstructure of hardened cement paste [13], [34], [38].

3.3.1 Standard consistency.

Various studies indicate that the use of wood waste ash as a partial substitute for cement in blended cement leads to a higher water requirement to attain a standard level of cement paste consistency. Typically, the amount of water needed for wood waste ash/OPC blended cement paste increases proportionally with the percentage of wood waste ash utilized as a binder replacement. The reason for this augmented water demand is linked to the more substantial specific surface area of the porous wood waste ash particles relative to OPC particles [34].

3.3.2 Initial and final setting times.

Using wood waste ash as a partial replacement for cement material in wood waste ash/OPC blended cement can result in delayed cement setting. This means that longer initial and final setting times of blended cement paste are necessary. The level of cement substitution with wood waste ash influences the degree of setting time delay [12], [35]. However, up to 30% of the total binder's weight, the initial and final setting times of the blended cement paste remain within the limits prescribed in the standard code of practice BS 12:1978 [4]. Researchers have found that the presence of wood waste ash, which is less reactive than OPC in blended cement, is the cause of the retardation rate of cement hydration, leading to the delay in the blended cement paste setting.

A longer setting time is a desirable property of blended cement as it allows for better workability of the paste. Moreover, the lower hydration heat of the blended cement due to the lower hydration rate, as previously mentioned, makes wood waste ash/OPC blended cement paste suitable for various applications. This is an important feature as it enables low heat development that balances any stress created by temperature differential, such as in mass concreting work.

3.3.3 Soundness.

When wood waste ash is employed as a partial substitute for cement in blended cement paste, the degree of soundness is notably elevated. As the proportion of wood ash used for cement replacement increases from 0 to 30%, the soundness of the blended cement paste rises proportionally. The most sound blended cement paste with a measurement of 1.45 mm is achieved when cement is substituted with wood ash at 30%, in line with the maximum allowable soundness of 10mm as stipulated by BS 4550 [4], [34], [36].

3.3.4 Calorimetric and heat evolution characteristics.

According to a study conducted by Rajamma et al. [37], the heat development properties of blended cement made with wood waste fly ash and ordinary Portland cement (OPC) were examined. The experiment involved using wood waste fly ash as a partial substitute for OPC in cement, with varying levels of substitution ranging from 0% to 30%. The results indicated that the blended cement paste sample reached a steady temperature of 24°C within 3 days of mixing. The cement paste containing wood fly ash reached its peak temperature faster than neat OPC without wood fly ash, which reached a peak temperature of 40°C.

The experiment also demonstrated that the peak temperature attainable by wood fly ash/OPC blended cement pastes decreased with increasing levels of cement paste replacement with wood waste fly ash. The peak temperature of all wood fly ash/OPC blended cement pastes with wood fly ash levels of cement replacement between 5% and 30% were lower in comparison to neat OPC paste.

The observed difference in the hydration rate and the shift in the peak of hydration temperature to the clean ordinary Portland cement (OPC) paste was due to the variations of alkali and chlorine content of wood waste fly ash used. It was also observed that the dilution of OPC content using wood waste fly ash as a partial substitution of OPC in the blended cement paste contributes towards lowering the hydration rate of the cement pastes and the corresponding decrease in peak temperature attainable by wood waste fly ash/OPC blended cement [36].

3.4 Microstructure of Cement Paste Matrix

A thorough analysis was carried out on the micro-structure of concrete mixes containing 0% (pc – 01 N) and 10% (pc – 03 N) of wood waste ash by total binder weight [12]. The findings revealed a significant decrease in the porosity of the hardened mortar for the latter concrete mix. Furthermore, the inclusion of 10% wood waste ash as a replacement for ordinary Portland cement in the concrete mix formula resulted in a considerable reduction in the percentage of non-hydrated cement and portlandite, while the amount of calcium silicate hydrate (CSH) gel in the concrete mix increased. This indicates a robust pozzolanic reaction between the reactive silica in wood waste ash and the portlandite compound produced by cement hydration.

XRD analysis of hardened wood waste fly ash blended cement paste indicated that the calcium silicate peaks in the blended cement paste with 10% wood waste fly ash of total binder weight were more pronounced than those with 30% wood waste fly ash. Furthermore, the highest intensity of the calcium silicate peak in neat OPC paste was observed at 28 days of curing [39].

4. Factors Influencing the Quantity and Quality of Wood Ash

When raw wood waste is incinerated, it produces wood ash that can be repurposed as a component of concrete and blended cement paste. However, various factors including the heat treatment temperature, tree species from which the wood waste originated, combustion technology used, and furnace thermodynamics can affect the characteristics of the wood ash. Therefore, it is crucial to analyze and understand the properties of the ash produced before utilizing it in cement production.

The temperature at which wood waste is incinerated significantly impacts the yield and chemical composition of the resulting wood ash. Combustion at temperatures over 1000°C leads to lower ash yield and reduced carbonate content due to compound decomposition. Meanwhile, combustion at temperatures under 500°C results in a higher concentration of carbonate and bicarbonate compounds, particularly calcite ($CaCO_3$). At higher incineration temperatures, oxide compounds like quicklime (CaO) become more prevalent in the chemical phase of the wood ash. As a result, the alkalinity of the ash decreases due to a reduction in carbonates and bicarbonates chemical species. Additionally, the concentration of light metallic elements like potassium, sodium, and zinc in wood waste ash decreases as the combustion temperature increases [2].

The origin and kind of tree from which wood waste is generated has a notable impact on the chemical makeup of resulting wood ash. To determine whether wood ash can be used as a replacement for cement, it is important to consider the composition of essential oxide compounds, like silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3), and quicklime (CaO), which can vary between different tree species.

In addition, the method of combustion employed also affects the physical and chemical properties of wood ash. For instance, grate-fired furnaces produce coarser wood ash that settles as bottom ash in the combustion chamber, whereas more advanced fluidized bed furnaces generate primarily fine fly ash with a finer particle size grading and only a small amount of coarse ash retained. Thus, choosing the appropriate combustion technology is a critical factor to consider when contemplating wood ash as a constituent material in cement production.

5. Durability Properties of Wood Ash

The relevant properties currently under investigation include acid attack resistance, water absorption, chloride permeability, corrosion current, electrical resistance, and alkali-silica reaction (ASR). These properties are critical factors in the assessment of materials for various applications in business and academic settings. It is essential to evaluate these properties to determine the material's durability, reliability, and overall performance in different environments. Hence, a comprehensive understanding of these properties is necessary to develop high-quality materials that meet the required standards.

5.1 Resistance against acid attack

A study was conducted by Udoeyo et al. [4] to explore how concrete made with wood waste ash holds up against acid attacks. The researchers created two sets of concrete samples with the same mix ratio of 1 part binder, 2 parts sand, 4 parts gravel, and a water-to-cement (w/c) ratio of 0.65. The first set contained neat OPC as a binder, while the second set had 85% of the total binder weight as cement and 15% as wood waste ash. The samples were then submerged in a 20% concentrated nitric acid solution, and their weight loss was measured at different time intervals over 70 days. Both sets of samples showed a decrease in mass, but the samples containing 15% wood ash as a binder experienced a less pronounced mass decrease compared to the control samples with no wood ash.
Overall, concrete samples made with wood waste ash are vulnerable to acid attack, although the extent of the effect varies depending on the type of acid. For example, concrete containing wood waste ash is less severely affected by sulphuric acid than concrete without wood waste ash [12].

5.2 Water absorption

The research findings of Elinwa et al. [12] and Udoeyo et al. [4] have revealed that the addition of wood waste ash as a cement replacement material within the range of 5% to 30% has the potential to result in a reduced level of water absorption for both concrete and mortar mixes. Such a reduction in water absorption has significant implications for the durability and long-term performance of such mixes. This finding is of particular relevance in the construction industry, where the use of sustainable materials is a growing concern. The inclusion of wood waste ash as a replacement material for cement can not only contribute to the reduction of waste, but it can also enhance the performance of concrete and mortar mixes.

5.3 Chloride permeability

In a study by Wang et al. [36], it was discovered that the addition of coarse particle size wood waste ash at 25% in air-mix concrete did not considerably reduce the chloride permeability property of the concrete. However, utilizing wood waste/coal blended fly ash in partial substitution of cement significantly aided in reducing the chloride permeability property of the concrete mix.

Moreover, in a separate study by Horsakulthai et al. [40], the inclusion of finely ground wood ash as partial cement replacement in concrete displayed an improvement in resistance against chloride penetration and a reduction in the chloride diffusivity coefficient.

6. Compressive Strength of Wood Ash

According to various studies, such as those referenced in [4], [12], [34], [35], incorporating wood waste ash at 5% and 30% into concrete mixes as a substitute for cement can lower compressive strength across all curing durations. This is because wood waste ash particles tend to function more as a filler material in the cement paste matrix, rather than as binding agents [4]. Consequently, increasing the amount of ash utilized as a cement replacement can elevate the surface area of filler material, leading to a reduction in cement and a subsequent decrease in strength. Most experts concur that the optimal compressive strength is achieved when wood waste ash replaces cement at a rate of between 10% and 20% in concrete mixes.

7. Reuse and Recycling of Wood Waste Ash.

Based on research findings, it has been demonstrated that wood waste ash can serve as an efficient ingredient in the production of controlled low-strength material (CLSM). Furthermore, wood waste ash has been shown to enhance soil alkalinity and work as a natural fertilizer [2]. Studies have also indicated that wood waste ash possesses pollution control properties and can be utilized as a substitute for lime or cement kiln dust in the treatment of hazardous waste.

Many researchers have worked on the wood waste ash to explore its potential, however, none of them has researched the production, characterization, and testing of wood ash on this selected tropical tree varieties in which wood ash was gleaned. These are *Gmelina arborea* (Gmelina) wood, *Anacardium occidentale* (cashew) wood, *Parkia filicoidea* (locust bean) wood, and *Milicia excelsa* (iroko) wood ashes in Nigeria. The application of the findings of this research work would be of immense importance.

8. Conclusion and Future Scope

The environmental impact of wood waste ash is a grave concern, as it consists of extremely fine particles that can easily disperse in the air or contaminate groundwater by leaching heavy metals. The current method of disposal involves expensive landfilling techniques. However, a more cost-effective solution is to employ the ash as a pozzolan in concrete, or as a raw material in cement production. Research has proven that wood waste ash contains minerals and properties that are compatible with these purposes. Nonetheless, additional studies are required to apply this material on a commercial scale.

Data Availability
Data will be available on a special request.

Limitations
Lack of equipment and inadequate funding were the major factors that affected this research.

Conflict of Interest
We the authors confirm that there is no conflict of interest.

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None

Author's Contribution
Edet Bassey Bassey researched the literature, conceived the study, and drafted the manuscript. Dr. Celestine Mbakaan reviewed and edited the manuscript. All the authors approved the final version of the manuscript.

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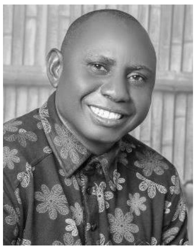

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