EFFECT OF THE PARTIAL REPLACEMENT OF CEMENT WITH WOOD ASH ON THE COMPRESSIVE STRENGTH OF CONCRETE

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EFFECT OF THE PARTIAL REPLACEMENT OF CEMENT

WITH WOOD ASH ON THE COMPRESSIVE

STRENGTH OF CONCRETE

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PLAGIARISM

The work **EFFECT OF THE PARTIAL REPLACEMENT OF CEMENT WITH WOOD ASH ON THE COMPRESSIVE STRENGTH OF CONCRETE** by AGBONZE, FRANK OSASENAGA with Matriculation Number ENG1905232 of the department of Structural Engineering, Faculty of Engineering, University of Benin, Benin City, Edo State, Nigeria has PASSED the PLAGIARISM TEST.

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CERTIFICATION

This is to certify that this work was carried out by AGBONZE, OSASENAGA FRANK with Matriculation number ENG1905232, of the department of Civil Engineering, Faculty of Engineering, University of Benin, Edo State, Nigeria.

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(Project Supervisor) Signature/date

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(Head Of Department) Signature/date

DEDICATION

I dedicate this project to God Almighty for the gift of life and his constant presence in my life and for always helping me navigate through difficult situations. I also dedicate this project to my parents, Mr. and Mrs. Agbonze for their constant love and support.

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My sincere gratitude goes to God Almighty for His protection over my life. Also, I would like to my project supervisor, Engr. Ehi Oria-Usifo for his expert guidance, understanding, and unwavering support in carrying out this work; his invaluable insights, constructive feedback, and encouragement have been instrumental in shaping this project. I would also like to extend my gratitude to the Head of Civil Engineering Department, University of Benin, Engr. Prof. Mrs. Ngozi Ihimekpen. I am also grateful for the guidance, mentorship, and assistance of all the Civil and Structural Engineering academic staff, especially Prof. Izinyon, Dr. A. I. Agbonaye, Engr. Mrs. Gloria E. Evbaru Okhuaihesuyi, Dr. Idowu Ilaboya, Engr. Dr. Mrs. Ngozi Kayode Ojo, Engr. Ehi Oria-Usifo, Engr Omosefe Blessing Eghosa, Engr. U. K. Ogbonna, Engr. Osasu Osamuyi, Engr. Mrs. Ambrose Agabi Esther, Prof. Ogeneale Orie, Engr. Dr Uchenna Ukeme, Prof. S. O. Osuji, Prof. A.N. Aniekwu, Engr. Prof. H. A. P Audu, Engr. Prof. J. O. Okovido, Engr. Prof. S. D. Lyeke, Dr. R. I. Umasabor, Dr. E. Nwankwo, Engr. Dr. R. O. Ogirigbo, Dr. L. O. Bobor, Engr. S. A. Adegbemileke, Engr. J. O. Ogbeide, Engr. Dr. P. N. Ogbeifun, Engr. O. Oriakhi, Engr. C. Okolie.

To my parents, MR and MRS Agbonze and my brothers; Williams, Osazee, Ikponmwosa, Nosa, and to my friends who also helped emotionally morally and academically Emperor, Precious, Oreoluwa, David, Iwinosa I express my immense gratitude because you all have been my strongest support system and I don’t take it for granted.

ABSTRACT

As sustainability becomes an essential focus in modern construction, the exploration of alternative materials and the reuse of industrial waste have gained increasing attention. This study examines the feasibility of using wood ash (WA) as a partial replacement for Ordinary Portland Cement (OPC) in the production of Grade 25 concrete, assessing its effects on workability and compressive strength.

Concrete samples were produced using a 1:1:2 mix ratio with a 0.41 water–cement ratio, incorporating 0%, 5%, 10%, 15%, and 20% replacements of cement by wood ash. Tests conducted included particle size distribution, slump test, compressive strength test, and water absorption test, with evaluations carried out at 7, 14, and 28 days of curing.

The results revealed a consistent reduction in workability as wood ash content increased, with slump values decreasing from 30 mm (control) to 0 mm at 20% replacement. Compressive strength results showed that 5% replacement yielded comparable performance to the control mix (32.49 N/mm^2 vs. 32.51 N/mm^2), while higher replacement levels resulted in strength reduction.

Water absorption tests indicated varied permeability levels. The 5% replacement demonstrated an absorption rate of 6.21%, conforming to BS 1881-122:2011, while 10%, 15%, and 20% replacements recorded progressively lower values, with 20% achieving 1.25%, indicating excellent quality and durability.

Based on these findings, the study concludes that wood ash can effectively replace up to 5% of cement in structural concrete applications without significant compromise in strength or durability. Beyond this level, the decrease in strength suggests that higher replacements are more suitable for non-structural uses, such as blocks or pavements, where lower strength requirements apply.

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CHAPTER ONE

INTRODUCTION

1.1 Background of Study

Concrete is the most widely used construction material in the world. Its popularity stems from its versatility, durability, and relatively low cost compared to other building materials. At the heart of concrete production is cement, which serves as the binding agent that reacts with water and bonds aggregates together to form a hard, stone-like mass. Despite its central role in infrastructure development, cement production has become a major environmental concern. It is estimated that the manufacture of cement contributes between five and eight percent of global carbon dioxide emissions. This is because large amounts of fossil fuels are consumed during clinker production, and limestone calcination releases additional carbon dioxide. With global demand for cement projected to rise due to rapid urbanization and population growth, these environmental challenges are expected to intensify.

Beyond the environmental implications, the cost of cement is another critical issue, particularly in developing countries such as Nigeria. Cement is an energy-intensive product, and fluctuations in energy prices directly affect its market cost. For many local builders and small-scale housing projects, the high price of cement limits access to quality construction materials. This has created an urgent need to identify alternative or supplementary materials that can partially replace cement without compromising the structural performance of concrete.

In this context, attention has increasingly turned toward industrial and agricultural by-products that are otherwise treated as waste. Fly ash, rice husk ash, and silica fume have already been widely researched and applied. More recently, wood ash, a residue obtained from the burning of wood in power plants, sawmills, and domestic stoves, has gained recognition as a potential supplementary cementitious material. Large amounts of wood ash are generated every year, and in many cases, the ash is simply dumped in open landfills or used as soil amendment, creating disposal challenges. However, its chemical composition—which often includes calcium oxide, silica, and alumina—suggests that it may play a useful role in cementitious systems.

Several studies have reported that incorporating wood ash in concrete can influence fresh and hardened properties. At low replacement levels, wood ash may act as a filler, improving packing density and slightly enhancing strength. It may also participate in pozzolanic reactions, where reactive silica combines with calcium hydroxide to produce additional calcium silicate hydrate (C–S–H), the main strength-giving compound in cement paste.

1.2 Statement of the Problem

The heavy dependence of the construction sector on cement presents both environmental and economic challenges. Cement production is not only energy-intensive but also a major contributor to greenhouse gas emissions, while simultaneously exhausting natural limestone deposits. Rising cement prices further burden construction projects, especially in developing countries where infrastructure development is most urgently required.

Wood ash is generated in large quantities as a waste product from sawmills, biomass plants, bakeries, and domestic kitchens. In most cases, this ash is discarded without proper disposal measures, leading to soil pollution, water contamination, and air quality issues. The combination of high cement costs and the environmental challenges of wood ash disposal creates a pressing need for alternative solutions.

The specific problem addressed in this study is whether wood ash can serve as a partial replacement for cement in concrete without compromising its compressive strength and overall performance. Addressing this question is essential to reducing both the environmental footprint and the economic burden associated with cement use in Nigeria.

1.3 Aim and Objectives

The aim of this project is to determine the effect of using wood ash (WA) as a partial replacement for cement in concrete production.

The specific objective includes;

i To source and prepare the wood ash (WA).

ii To develop concrete mix design with varying proportions of WA (0%, 5%, 10%, 15% and 20%) replacement of cement.

iii To cast concrete samples using the developed mix designs and cure the samples under controlled conditions to ensure consistent hydration and strength development.

iv To analyze the test results to determine the impacts of wood ash (WA) on the mechanical properties and flexural strength of concrete.

1.4 Scope of Study

i The scope of this study involved sourcing and obtaining wood ash (WA) from burnt wood and sieving it using a 200 mm BS sieve.

ii Ordinary Portland Cement (OPC) of grade 42.5, angular granite coarse aggregate, and riverbed sand fine aggregate were used.

iii A preliminary concrete mix design targeting a compressive strength of C25 was adopted, using a free water-cement ratio of approximately 0.41 and a mix proportion of 1:1:2 for cement, fine aggregate, and coarse aggregate, respectively.

iv Fresh and hardened concrete tests (slump and compressive strength tests, respectively) were conducted, and the performance of wood ash in concrete was evaluated by analyzing the test results.

1.5 Justification of Study

With cement prices steadily increasing and its production linked to high environmental costs, there is a pressing need to investigate alternative binders that are both affordable and eco-friendly. Wood ash, a readily available residue from household and industrial combustion, offers a dual benefit: it reduces reliance on cement while providing a productive use for a common waste material. Incorporating wood ash into concrete not only lowers costs but also promotes sustainable construction and better waste management. Furthermore, this study seeks to contribute to the relatively limited research on wood ash applications in construction, especially within the context of developing nations.

CHAPTER TWO

LITERATURE REVIEW

2.1 Synopsis

Concrete continues to serve as the foundation of modern infrastructure because of its adaptability, strength, and affordability. Despite these advantages, its primary binder—cement—poses serious environmental challenges, largely due to the high energy required for clinker production and its significant share of global carbon dioxide emissions. In response, scholars and engineers have focused on the use of supplementary cementitious materials (SCMs) that can partly replace cement while still delivering acceptable concrete performance.

As a by-product of burning wood and biomass for energy or industrial purposes, wood ash is readily available in many regions, especially in countries with significant sawmill operations. In most cases, wood ash is considered waste and disposed of in landfills, causing environmental problems. Its incorporation into concrete therefore represents both a method of waste recycling and a strategy to reduce cement demand.

This chapter reviews the properties of materials used in concrete, with special emphasis on wood ash. It explains the physical, chemical, and mineralogical characteristics of wood ash, its pozzolanic potential, and its influence on fresh and hardened concrete properties. The sustainability benefits of using wood ash in concrete are also highlighted, as they form the justification for this research.

2.2 Terminologies

2.2.1 Materials and Properties

Concrete is essentially a composite material consisting of cement, aggregates, water, and sometimes admixtures. Each constituent contributes specific qualities to the mix, and any alteration to the composition inevitably affects the behavior of the concrete. To fully appreciate the role of wood ash as a cement replacement, it is important to first understand the nature of these materials.

i. Wood

ii. Binding Materials

iii. Aggregates Mixing

iv. Water

2.2.1.1 Wood

Throughout history, wood has served as one of the most important construction resources, appreciated for its strength, ease of use, and widespread availability. Beyond its use as a structural material, it remains a major energy source, particularly in developing nations where biomass fuels supply a large share of domestic and industrial energy needs. The burning of wood produces substantial amounts of residue, commonly known as wood ash.

The physical and chemical composition of wood ash is influenced by several factors, including the species of tree, the type of soil in which it was grown, the specific part of the tree burned, and the combustion method. Typically, hardwoods generate ash with relatively higher calcium oxide content, whereas softwoods often yield ash with more potassium-based compounds. Similarly, ash derived from industrial furnaces differs in quality and consistency from ash produced by small-scale or open burning.

Because of this variability, wood ash does not always perform uniformly when used in cementitious applications. Nonetheless, it usually contains important oxides such as calcium, silica, alumina, and iron, which are also central to the chemistry of cement.

Figure 2.1: wood ash

2.2.1.2 Binding Materials

Cement is the most common binder in concrete technology, valued for its capacity to chemically react with water and form a hardened matrix that secures aggregates into a solid mass. The major phases in cement include tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), and tetracalcium aluminoferrite (C_4AF). These compounds hydrate to form calcium silicate hydrate (C–S–H) gel, the main strength-giving phase, along with calcium hydroxide and other hydration products.

Although cement is indispensable in modern construction, its production contributes significantly to global CO_2 emissions—estimated between 5% and 8% of total anthropogenic emissions. Furthermore, cement manufacture is energy-intensive, requiring high kiln temperatures. For this reason, researchers have sought to partially replace cement with SCMs such as fly ash, silica fume, rice husk ash, and more recently, wood ash. These materials often contain reactive silica and alumina, which can combine with calcium hydroxide to form additional C–S–H, enhancing concrete durability while reducing the cement content.

Table 2.1: Approximate limits to some chemical composition present in cement

	FUNCTIONS	COMPOSITION (%)
Lime (CaO)	Controls strength and soundness. When absent it reduces strength and setting time.	60 - 65
Silica (SiO_2)	This gives strength to cement. However, excess of it causes slow setting.	17 - 25
Alumina (Al_2O_3)	This is responsible for quick setting, if in excess, it lowers strength.	3 – 8
Iron Oxide (Fe_2O_3)	Gives color and helps in fusion of different ingredients.	0.5 – 6
Magnesia (MgO)	Affects color and hardness, if in excess it causes cracks in mortar and concrete and unsoundness.	0.1 – 4
Silica (SO_3)	Makes cement sound	1 – 3
Soda and Potash (Na_2O+K_2O)	They are residues, if in excess it can cause efflorescence and cracking.	0.5 – 1.3

2.2.1.3 Aggregates

Aggregates form the bulk of concrete and significantly affect both fresh and hardened properties. They are usually divided into fine aggregates (sand, with particles passing through 4.75 mm sieve) and coarse aggregates (gravel or crushed stone retained on a 4.75 mm sieve).

Fine aggregates fill the spaces between coarse aggregates and influence workability and finish. River sand is commonly used, but in some regions, crushed stone sand or manufactured sand serves as a substitute. The particle shape of fine aggregates matters: rounded particles improve workability, while angular particles provide better interlock and strength.

Coarse aggregates, on the other hand, provide bulk and stability. Sizes range from 9.5 mm up to 37.5 mm, depending on the application. Well-graded aggregates reduce voids, enhance packing, and lower the water requirement of the mix. Conversely, poorly graded aggregates may produce porous, weaker concrete. Contaminants such as clay, organic matter, or unsound particles (like coal and wood fragments) must be avoided as they can hinder hydration or weaken the bond between paste and aggregate.

2.2.1.3.1 Fine Aggregate

When aggregates are passed through a 4.75 mm sieve, the material that goes through is referred to as fine aggregate. Typically, natural sand serves as the fine aggregate, although silt and clay are also included in this category. Loamy soils, which contain a mixture of sand, silt, and clay, can also contribute to the fine fraction. In concrete production, fine aggregates are critical because they fill the voids between coarse particles and enhance the mix’s workability.

According to ASTM C33 (2016), fine aggregates may consist of either natural sand or manufactured alternatives such as crushed stone sand. Particle shape plays a significant role: rounded sand grains generally improve flow and ease of placement, whereas angular grains from crushed stone provide stronger interlocking, which contributes to better structural integrity (Kumar & Singh, 2020).

Table 2.2: Size Variation of Fine Aggregate

FINE AGGREGATE	SIZE VARIATION (mm)
Coarse Sand	2.0mm – 0.5mm
Medium Sand	0.5mm – 0.25mm
Fine Sand	0.25mm – 0.06mm
Silt	0.06mm – 0.002mm
Clay	< 0.002mm

2.2.1.3.2 Coarse Aggregate

Materials retained on a 4.75 mm sieve are referred to as coarse aggregates, which include gravel, crushed stones, and cobbles. The choice of maximum aggregate size depends on the project requirements. For example, concrete mixes intended for general structural applications often employ 40 mm aggregates, while higher-strength concrete tends to utilize smaller sizes, such as 20 mm (PCA, 2015). Because coarse aggregates make up the bulk of the volume in concrete, they play a vital role in providing structural stability, overall strength, and long-term durability (Siddique, 2020). Consequently, selecting the right size and type of aggregate is essential for ensuring the desired performance of the concrete (PCA, 2015).

Generally, larger particles reduce workability and may require higher water content to achieve proper consistency. The distribution of particle sizes, or gradation, is equally important. A well-graded aggregate blend fills internal voids more efficiently, resulting in denser and stronger concrete. Conversely, poorly graded aggregates can produce porous mixtures with lower strength. Properly graded aggregates, containing a wide range of particle sizes, help fill the voids between larger particles, resulting in a denser, more cohesive concrete. The typical size ranges for various coarse aggregates are outlined as follows:

Table 2.3: Size Variation of Coarse Aggregate

COARSE AGGREGATE	SIZE VARIATION (mm)
Fine Gravel	4mm – 8mm
Medium Gravel	8mm – 16mm
Coarse Gravel	16mm – 64mm
Cobbles	64mm – 256mm

2.2.1.4 Mixing water

Water triggers the hydration process in cement and helps achieve workability in fresh concrete. Ideally, potable water is used in construction. Impurities such as chlorides, sulphates, or organic matter may interfere with hydration reactions or promote reinforcement corrosion. High chloride levels, for example, can destabilize the passive oxide layer on steel reinforcement, leading to corrosion. Similarly, excessive sulphates may react with calcium aluminate hydrates, causing expansive cracking known as sulphate attack.

Standards such as BS EN 1008 and ASTM C1602 specify permissible limits for impurities in mixing water to ensure that the final concrete maintains durability and safety.

Table 2.4: Limit of impurities in mixing water (mg per litre, ppm) (Neville and Brooks, 2008)

Impurity	BS 3148:190	BS EN 1008:2002	ASTM C 1602/C

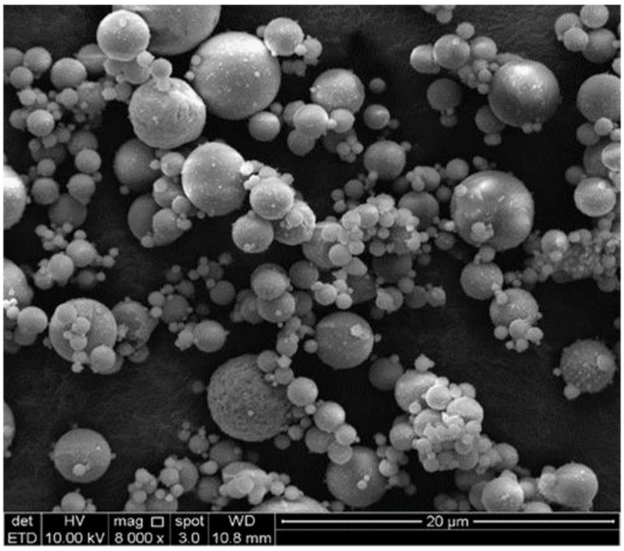
			1602M-06
Chloride ion:			
Prestressed concrete	500	500	500
Reinforced concrete		1000	1000
Plain concrete		4500	2000
Sulphate	1000 (SO3)	2000 (SO3)	3000 (SO4)
Alkali	1000	1500	600

2.3 Characteristics of Wood Ash

2.3.1 Physical Properties

Wood ash particles are generally lighter, irregular in shape, and more porous than cement grains. Their color ranges from light grey to dark black depending on combustion efficiency. The bulk density of wood ash is usually lower than cement, which can reduce the unit weight of the resulting concrete mix. Due to their fine and porous nature, wood ash particles absorb more water, increasing the water demand of the mix. This explains the reduction in slump observed in wood-ash-modified concretes.

The ranges of specific surface area, mean particle size, density, and pH values of various wood ashes, as reported in the literature, are summarized in Figure 2 (which includes FESEM images of wood ash and fly ash, illustrating their morphological differences).



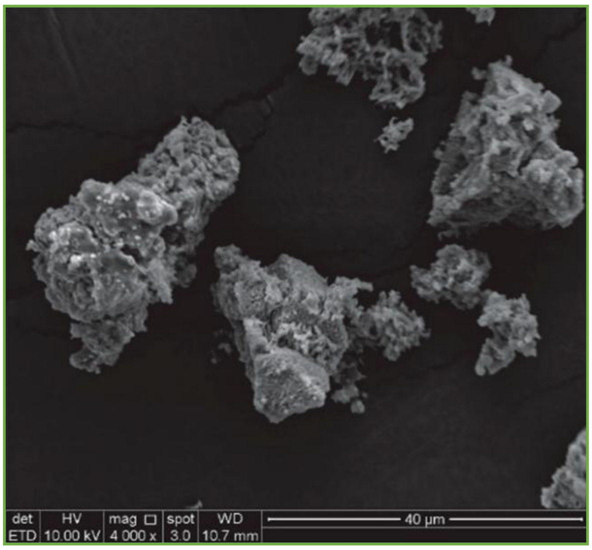


Figure 2.2a: FESEM images of wood ash **Figure 1.2b: fly ash**

(reprinted from Abdulkareem et al., with permission from AIP Publishing).

2.3.2 Chemical Properties

The chemical composition of wood ash varies significantly with fuel source and combustion conditions. Common oxides present include calcium oxide, silica, alumina, iron oxide, potassium oxide, and magnesium oxide. In general, the calcium content is relatively high, which supports cementitious behavior, while the silica content may contribute to pozzolanic activity. However, the variability makes it difficult to standardize performance.

Standards for pozzolanic materials (e.g., EN 450-1 for fly ash) require that the sum of silica, alumina, and iron oxide exceed 70%. Many wood ashes fall short of this benchmark, limiting their classification as strong pozzolanic materials.

2.3.3 Mineralogical Analysis

Investigations carried out with techniques such as X-ray diffraction (XRD) and scanning electron microscopy (SEM) indicate that wood ash is a complex material containing both crystalline and amorphous phases. The crystalline portion generally includes minerals like quartz, calcite, and various oxides, while the amorphous fraction contributes reactive silica and alumina that can participate in pozzolanic reactions. The relative proportions of these phases are influenced by the type of biomass and the combustion temperature.

SEM observations typically display particles that are porous, irregularly shaped, and rough-surfaced—quite unlike the smoother, spherical grains found in fly ash. These characteristics help explain why concrete mixes incorporating wood ash tend to have greater water demand and reduced workability.

2.3.4 Loss on Ignition

Despite these differences in the standard methods, many studies in the literature do not specify the temperature at which LOI is measured, and in some cases, the stated measurement temperatures were between 750 and 1000^0C. According to ASTM C618, if acceptable performance results are provided, the use of Class F fly ash with loss on ignition of up to 12% is acceptable. (Ngueyep et al 2019). State that if the LOI value is greater than 12%, the pozzolanic activity reduces due to the unburnt carbon, and wood ash acts as a filler in the concrete mixture.

2.3.5 Pozzolanic and Hydraulic Properties

Pozzolanic activity is defined as a reaction between calcium hydroxide and alumina silicates, resulting in a hydration product with binding properties. In EN 450-1, the pozzolanic property is determined by the sum of the amounts of SiO_2, Fe_2O_3, and Al_2O_3, also known as pozzolanic oxides, and this sum must be greater than 70%. According to the literature, the sum of pozzolanic oxides in wood ashes varies in the range of 13.03% to 88.32%. Many studies have reported that wood ash shows pozzolanic behavior. (Elinwa et al 2016) reported pozzolanic properties due to the sum of pozzolanic oxide of sawdust ash being 73.55%. (Rajamma et al 2018) also observed pozzolanic activity using the Frattini test for wood fly ash, although the pozzolanic oxide content was 53.2%. Ramos et al. determined the pozzolanic properties of wood ash by replacing 20 wt% of Portland cement and determining the strength activity index according to EN 450-1.

On the other hand, some studies have reported no pozzolanic property. For example, Garcia and Sousa-Coutinho assessed the pozzolanic activity of different wood fly and bottom ashes using the Frattini test, which showed no pozzolanic activity. Demis et al. attributed the lack of pozzolanic property to the low amount of SiO2 (31.8%) and high LOI (27%).

Materials that form hydration products as a result of chemical reactions with water have the ability to harden and maintain their strength and stability even under water after hardening and are defined as hydraulic binders.

2.4 Properties of Concrete and Mortar Containing Wood Ash

2.4.1 Workability

One of the first observable effects of incorporating wood ash into concrete is the reduction in workability. Fresh mixes containing high proportions of wood ash often appear stiffer than conventional mixes, making placement and compaction more difficult. This behavior is attributed to the fine particle size and porous nature of wood ash, which significantly increase its surface area. A larger surface area demands more water for wetting, thereby reducing the amount of free water available for lubrication of the mix. In practice, this results in lower slump values, particularly when the replacement level exceeds 10%. Researchers have reported that the reduction in workability becomes more severe with increasing ash content, although the use of water-reducing admixtures such as superplasticizers can mitigate this effect.

Material and Cement Replacement Ratio	Properties	Results	Observed Effects of Wood Ash	References
Mortar 0, 5, 10, 15, 20, 25, and 30 wt%	Setting time Soundness Compressive strength	116–190 min (initial), 241–337 min (final) 0.70–1.45 mm 3.70–22.44 MPa (at 3–60 days)	-Pozzolanic activity -Increased water demand, setting time, and soundness -Optimum wood ash ratio: 10 wt%	[49]
Concrete 0, 10, 20, 30, and 40 wt%	Setting time Slump Compressive strength	100–436 min (initial), 160–789 min (final) 30–40 mm (w/b = 0.60, 0.66, 0.67, 0.68, 0.69) 8.59–24.15 MPa (at 28–60 days)	-Pozzolanic activity -Increased water demand and setting time -Optimum wood ash ratio: 20 wt%	[29]
Concrete 0, 5, 10, 15, 20, 25, and 30 wt%	Slump Compressive strength Flexural strength Water absorption	0–8 mm 12.83–28.66 MPa (at 3–90 days) 3.51–5.20 MPa (at 3–90 days) 0.14–1.05%	-Decreased workability (up to 20 wt%), and slump was not observed for higher levels -Optimum wood ash ratio: 5 and 10 wt%	[20]
Mortar 0, 10, 20, and 30 wt%	Slump Setting time Compressive strength Flexural strength	110–130 mm 120–150 min 22.59–43.31 MPa (on the 28th day) 3.39–6.98 MPa (on the 28th day)	-Pozzolanic activity -Acceptable strength results up to 20 wt% wood ash	[30]
Mortar 0, 10, and 20 wt%	Strength Activity Index Alkali–silica reaction (ASR) expansion	98–102% (at 28–90 days) 0.1643% for 10 wt% wood ash, 0.00669% for 20 wt% wood ash at 14 days	-Pozzolanic activity -Increased compressive strength -Decreased ASR expansion with increasing wood ash content	[8]
Mortar 0, 5, and 10 wt%	Compressive strength Flexural strength Resistance against chloride permeability	32.2–65.4 MPa (at 3–365 days) 8–11.5 MPa (at 3–365 days) Low (on the 78th day)	-No pozzolanic activity -Decreased strength with increasing wood ash content -12% improvement in compressive strength after 3 days -Slightly higher chloride permeability	[31]

Figure 2.3: Effects of wood ash incorporation on mortars and concretes

2.4.2 Setting Time

Wood ash has been found to alter the setting behavior of cement pastes and concrete. In many studies, the initial and final setting times increased as the replacement level rose. This is primarily due to two factors: the dilution of cementitious compounds and the presence of chemical constituents in the ash, such as phosphates and alkalis, that can interfere with normal hydration. Extended setting times can be advantageous in hot weather concreting, where rapid hydration may otherwise lead to premature stiffening and poor surface finish. However, in cold climates or in time-sensitive construction projects, longer setting times could delay formwork removal and finishing operations. For this reason, proper proportioning and quality control of wood ash are essential to balance its benefits and drawbacks with respect to setting behavior.

2.4.3 Soundness

Soundness refers to the ability of hardened cement paste to resist expansion after setting. In the context of wood ash, this property is heavily influenced by the oxides present. High levels of free lime (CaO) or magnesia (MgO) in the ash can hydrate slowly after the concrete has hardened, producing expansive compounds that may cause cracking or disintegration. While controlled combustion generally produces ash with stable oxides, uncontrolled burning, such as that occurring in open kilns or domestic stoves, may yield ash with unstable components. Therefore, soundness testing is crucial before using wood ash in structural applications. When properly processed and tested, however, wood ash can be safely used without compromising the dimensional stability of concrete.

2.4.4 Compressive Strength

Compressive strength is the most widely used indicator of concrete quality, and it is strongly influenced by the presence of wood ash. At low replacement levels—typically up to 5%—wood ash may not significantly affect strength. In fact, the filler effect of fine ash particles can enhance the packing density of the paste, leading to slightly improved strength in some cases. This is often attributed to the ability of fine particles to fill voids in the cement matrix, resulting in denser and less permeable concrete.

However, as the replacement level increases beyond 10%, compressive strength generally decreases. The decline is due to the reduced amount of cement available to form hydration products, coupled with the relatively low pozzolanic reactivity of most untreated wood ashes. At high replacement levels (15–20%), the cement paste may lack sufficient calcium silicate hydrate (C–S–H) gel to bind aggregates effectively, leading to weaker concrete. The rate of strength development is also slower in wood-ash-blended concrete compared to ordinary Portland cement concrete. Nevertheless, when the ash is finely ground or pretreated to enhance reactivity, it can contribute more positively to strength development. This shows that while untreated wood ash is best used in small amounts, processed ash has potential for broader application.

Empirical Framework

Below are some studies reviewed in relation to this project:

Omodara et al. (2014) examined how varying concentrations of wood ash affect the growth of different strains of Bacillus subtilis. They prepared ash solutions in distilled water ranging from 0% to 5% by weight, adjusted the pH from 9.6–9.8 down to 7.2 using 0.1M hydrochloric acid, and then used the filtrates to produce nutrient agar and broth media. Growth performance of five Bacillus subtilis strains was assessed on ash-amended agar using the pour-plate method at 35°C.

Rebeca et al., (2022) mentioned that the challenge of managing increasing industrial and household waste, combined with the high carbon footprint of cement manufacturing, has intensified the search for sustainable construction alternatives and waste utilization strategies.

Prabagar et al. (2015) investigated its use as a partial cement replacement in block production, reporting improvements in both strength and thermal insulation. In this regard, wood ash—a residue from biomass combustion—has been identified as a promising resource with multiple applications.

Similarly, Haider (2021) assessed its suitability as a replacement for fly ash in geopolymer concrete, broadening its potential within green construction.

Jonna et al. (2017) mentioned that beyond construction, wood ash has also proven valuable in agriculture. highlighted its role as a low-cost soil conditioner for smallholder farmers due to its nutrient content, particularly potassium and phosphorus.

Dora et al. (2020) expanded on this by studying the fertilizer potential of domestic wood ash in Ghana and evaluating extraction methods for nutrient recovery. These findings emphasize wood ash's contribution to a circular economy by turning waste into a useful product and reducing landfill dependency.

More recently, Ece et al. (2023) reviewed eco-friendly binders aimed at lowering the environmental burden of cement production. Their review noted that wood ash, particularly fly ash obtained from power plants and bakeries, is gaining attention as a sustainable binder, whether applied as a partial cement replacement or as an alkali-activated material.

Research Gap

The utilization of wood ash as a sustainable alternative to partially replace cement in concrete production has gained attention due to environmental and economic benefits. However, despite growing interest, existing studies predominantly focus on limited aspects such as short-term compressive strength or general material properties. There remains a lack of comprehensive research that investigates the impact of varying wood ash replacement ratios on both the mechanical performance and durability of concrete over extended periods.

Moreover, wood ash from different biomass sources, combustion techniques, and processing conditions exhibits significant variability in chemical composition and physical properties, yet most studies treat wood ash as a uniform material without accounting for these differences. This oversight leads to a gap in standardized understanding of how these variations affect the hydration process, microstructure development, and ultimately the compressive strength of the concrete.

Additionally, many investigations do not explore the interaction effects between wood ash and other supplementary cementitious materials or admixtures commonly used in concrete, leaving uncertainties about the combined influence on concrete behavior. There is also limited knowledge regarding the environmental impacts and long-term performance of wood ash-incorporated concrete, including resistance to chemical attack, freeze-thaw cycles, and carbonation.

Therefore, comprehensive studies that address these deficiencies—by evaluating the optimal wood ash replacement levels, characterizing wood ash from various origins, and assessing both mechanical properties and durability aspects—are essential to fully harness the potential of wood ash as a viable and reliable cement substitute in concrete production.

CHAPTER THREE

METHODOLOGY

3.1 Materials used

The materials that were utilized included Natural aggregate, cement, Wood ash and water**.**

3.1.1 Natural Aggregate

Coarse and fine aggregates were utilized, and were obtained from a store in Ugbowo, Benin City, Edo State.

3.1.1.1 Coarse Aggregate

In this study, granite was employed, available in different sizes and shapes. The focus was on angular granite, a frequently crushed type. Its sharp edges and corners contributed to the workability and strength of the concrete mix.

3.1.1.2 Fine Aggregate

Fine sand was used for this study, particularly sand sourced from the riverbed, ensuring it was free from debris and impurities. The particle size ranged from 5mm to 150mm.

3.1.2 Cement

The cement used was Ordinary Portland Cement (OPC) of grade 42.5, which was purchased from a store in Ugbowo, Benin City, Edo State.

3.1.3 Wood Ash

The wood ash (WA) utilized in the course of this experiment was obtained from burnt wood after which, was sieved using a 200mm BS sieve

3.1.4 Water

Water used for the concrete mix and curing was free from contaminants and any substances that could impede hydration. It was sourced from the civil/structural laboratory at UNIBEN, Benin City, Edo State.

3.2 Sample Preparation

Concrete samples were prepared using cubic molds measuring 100 mm on each side (10 cm) for various tests. To prevent concrete from sticking to the mold surfaces, the molds were thoroughly cleaned and coated with a lubricant (form oil). The molds were then assembled, and the bolts were tightened securely to prevent any leakage of cement paste during casting.

The wood ash sample was dried at a consistent temperature of 110 ± 5 °C until reaching a constant weight. After drying, it was cooled to room temperature in a desiccator before further use. The dried wood ash was then placed on the topmost sieve (200 µm) and mechanically shaken for approximately 10 to 15 minutes, or until the mass retained on each sieve became steady, indicating that the maximum amount of ash had been separated without significant loss. The fraction passing the 200 µm sieve was used for concrete batching.

3.3 Apparatus for laboratory Test

The tools, equipment and machines used during this study include: concrete mixer, compression testing machine, weighing machine, oven, shovel, a set of sieves, head pans, buckets, tamping rod, measuring tape, measuring cylinder, hand trowel, concrete moulds and head pan

3.4 Mix Design

The concrete mix design was carefully balances cement, sand, aggregate, and water to ensure the right strength and durability for construction was . These proportions are measured by weight and adjusted using volume batching, guaranteeing consistency in the final mixture.

Table 3.1, 3.2, 3.3 shows the mix design

Table 3.1: Mix Design for Grade 25 Concrete (Using Grade 42.5 Cement)

S/NO	ITEM	UNITS	Values
1	STAGE 1		
1.1	Characteristic strength	MPa	25
1.2	Standard deviation	MPa	4
1.3	Margin	MPa	6.56
1.4	Target mean strength	MPa	31.56
1.5	Cement grade		42.5
1.6	Aggregate type: coarse		Crushed
1.7	Aggregate type: fine		Uncrushed
1.8	Free water/cement ratio		0.41
1.9	Maximum free W/C ratio		NONE
2	STAGE 2		
2.1	Slump	mm	60-180
2.2	Maximum aggregate size	mm	20
S/NO	**ITEM**	**UNITS**	**Values**
2.3	Free-water content	Kg/m^3	225

3	STAGE 3		
3.1	Cement content	Kg/m^3	548.78
3.2	Maximum cement content (specified)	Kg/m^3	NONE
3.3	Minimum cement content (specified)	Kg/m^3	NONE
3.4	Modified free-water/cement ratio		NONE
4	STAGE 4		
4.1	Concrete density	Kg/m^3	2400
4.2	Total aggregate content	Kg/m^3	1626.3
5	STAGE 5		
5.1	Grading of fine aggregate		Zone 11
5.2	Proportion of fine aggregate	%	35
5.3	Fine aggregate content	Kg/m^3	562.21
5.4	Coarse aggregate content	Kg/m^3	1057.1
6	STAGE 6 - Trial Mix quantities	100mm cube	
S/NO	**ITEM**	**UNITS**	**Values**
6.1	Cement (kg)		548.78

6.2	Water (kg)		225
6.3	Fine aggregate		562.21
6.4	Coarse aggregate		1057.1
Mix Proportion = 1: 1: 2			

Table 3.2: Result from Concrete Mix Design

Quantities	Cement (kg)	Water (kg)	Fine Aggregates (kg)	Coarse aggregates (kg)
Per m^3 to the nearest kg	548.78	225	562.21	1057.1
Ratio	1	0.4	1	2

Table 3.3: Final Mix Design

Quantities	Cement (mm^3 x 10^6)	water (mm^3 x 10^6)	Fine aggregate (mm^3 x 10^6)	Coarse aggregate (mm^3 x 10^6)
Ratio	1	0.4	1	2
Per 100mm cube for 1 cube	0.55	0.18	0.56	1.057

3.3.1 Batching

The density of normal concrete is $2430 kg/m^3$. Since the volume of one cube is $0.001m^3$ (0.1m x0.1m x0.1m) for curing periods of 7, 14, 28 days and a partial replacement of 0%, 5%, 10%, 15% and 20% of coarse aggregate with crushed concrete.

Density = $\frac{mass\ (m)}{volume\ (v)}$ Eq. (3.5)

Number of cubes = 9 cubes for each curing period x 5 replacements = 45 cubes

Total mass of cube to cast = 45 × 2.43 = 109.35kg

A mix of 1:1:2 mix (total 1+1+2 = 4). Therefore, batching will be;

Cement: $\frac{1}{4} \times 109.35 = 27.34kg$

Sand: $\frac{1}{4} \times 109.35 = 27.34g$

Aggregate: $\frac{2}{4} \times 109.35 = 54.68kg$

At each replacement (for 9 cubes): For

12 cubes: 9 × 2.43 = 21.87kg

Cement: $\frac{1}{4} \times 27.34 = 6.84kg$

Sand: $\frac{1}{4} \times 27.34 = 6.84kg$

Aggregate: $\frac{2}{4} \times 54.68 = 27.34kg$

The table below shows the mix proportions adopted for cube specimens incorporating varying levels of crushed concrete replacement. The table outlines the water-to-cement (W/C) ratio, cement content, fine aggregate (sand), natural coarse aggregate (granite), and wood ash quantities used at replacement levels ranging from 0% to 20%. This systematic variation provides the basis for evaluating the influence of wood ash substitution on the mechanical and workability properties of concrete.

Table 3.4: Mix proportion for cubes

Crushed concrete replacement (%)	W/C Ratio	Cement (kg)	Sand (kg) (Fine aggregate)	Granite (kg) (Natural coarse aggregate)	Wood Ash (kg)
0%	0.40	6.84	6.84	27.340	0
5%	0.40	6.84	6.84	25.973	1.367
10%	0.40	6.84	6.84	24.606	2.734
15%	0.40	6.84	6.84	23.239	4,101
20%	0.40	6.84	6.84	21.872	5.468

3.4 Mix Proportion

After determining the mix ratio and water-cement ratio, concrete specimens were cast into 100mm × 100mm × 100mm cubes, incorporating wood ash at varying replacement levels (0%, 5%, 10%, 15% and 20%). The cement, fine aggregate, coarse aggregate, and wood ash were thoroughly mixed before adding water. The fresh concrete was then poured into molds and vibrated to improve compaction and eliminate voids. After setting for 24 hours, the specimens were carefully removed from the molds and placed in a curing water tank, where they remained for proper hydration and strength development. Finally, compression tests were performed at 7, 14, and 28 days to assess their structural performance.

3.4 Laboratory Test of the Physical Properties of Aggregates

In this study, the physical properties analyzed included Particle Size Distribution and Aggregate Impact Value, both of which play a crucial role in assessing the quality and performance of aggregates in concrete production.

3.4.1 Particle Size Distribution

In this test, a substance is divided into many particle size classifications of decreasing sizes using a succession of test sieves. The starting mass of the material is connected to the mass of the particle retained on the different sieves. Both numerical and graphical data are provided regarding the proportions of each sieve that pass through. The purpose of the test was to ascertain the coarse aggregate's (granite) particle size distribution in accordance with (BS EN 993-1-1997).

Apparatus

Sieves with different mesh sizes, weighing balance, cleaning brush, scoop and pan

Procedure

1. The sieves were arranged from largest to smallest aperture size, forming a sieving column with a pan and lid.
2. The sample was poured into the column, and manual shaking was performed thoroughly.
3. Sieves were removed one by one, starting from the largest aperture size (topmost), ensuring no material was lost in the process.
4. Any material that passed through each sieve was returned to the column, and the process was repeated for each sieve.

5. The retained material in the largest sieve was weighed, and its weight was recorded. This procedure was carried out for all sieves, with individual weights documented.
6. The material that remained in the pan was also weighed and recorded.
7. The mass retained on each sieve was then calculated as a percentage of the original dry mass, after which, the cumulative percentage of the original dry mass passing through each sieve was obtained.

$$\frac{Wpassing}{Wtotal} \times 100\% \qquad \text{Eq. (3.6)}$$

3.5 Testing the Properties of Fresh Concrete

3.5.1 Slump Test

The slump test was conducted in accordance with BS 1881-102:1983, which establishes the method for evaluating the workability of cohesive concrete with medium to high consistency. A true slump, where the concrete remained intact and symmetrical, was considered valid. This test served as a quality control measure, ensuring that the materials supplied to the mixer met the necessary standards. Variations in slump height could indicate changes in moisture content or aggregate quality, such as a shortage of fine aggregates. Significant deviations—whether too high or too low—provided an immediate warning, allowing the mixer operator to make timely adjustments.

Apparatus

i. Standard frustum-shaped mold, complying with BS 1881-102:1983
ii. Flat steel base plate
iii. Standard tamping rod and graduated steel rule (0–300mm, in 5mm increments)
iv. Scoop, approximately 100mm wide

Procedure

1. The mold's interior surfaces were cleaned and lightly oiled to prevent fresh concrete from adhering.
2. The mold was placed on the base plate and secured firmly.
3. The cone was filled in three layers, with each layer compacted using 25 strokes of the tamping rod.
4. Once filled, the top surface was leveled by rolling the tamping rod across it.
5. The mold was then carefully lifted to expose the concrete, and the unsupported slump was measured and recorded.

3.6 Determination of Compressive Strength

3.6.1 Casting cubes

The concrete specimens were cast in wooden molds measuring 100mm cubes, in compliance with BS 1881-3:1970. The molds were carefully assembled, with screws tightened to prevent any leakage of cement paste. Their inner surfaces were cleaned and oiled to minimize adhesion between the concrete and the mold. Concrete was poured into the molds in three layers, with each layer compacted using a vibrating table to expel entrapped air and achieve full compaction without segregation. The molds were filled to overflowing, and excess concrete was removed using a steel rule in a sawing motion. A trowel was used for surface finishing, ensuring a smooth and uniform surface.

Figure 3.1: Casting of Cubes

3.6.2 Curing cubes

After 24 hours in the mold, the concrete specimens were carefully removed and marked with a waterproof marker for easy identification. They were then transferred to the curing tank in the structural laboratory, where they underwent curing for 7, 14, and 28 days to ensure full strength development. The curing process involved regulating both temperature and moisture flow, maintaining optimal conditions for hydration. The primary objective was to keep the concrete as close to a saturated state as possible, allowing cement hydration products to fully occupy the initial water-filled spaces in the fresh paste, ensuring durability and structural integrity.

3.6.3 Compression test

The compression test was conducted in the structural laboratory following the curing period. Once the curing duration was completed, the concrete cubes were removed from the curing tank and wiped to eliminate surface moisture, ensuring accurate testing conditions. Each cube was then positioned in the testing machine, with its cast face in direct contact with the machine's plates.

Figure 3.2: Compression Test on Hardened Cube

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Results

4.1.1 Sieve Analysis

The sieve size conforming to the BS 1377-2-1990 specifications for test sieves was utilized for the sieve analysis. The grading curves as shown in Figure 4.1 demonstrate the graphical representation of the sieve analysis results.

Table 4.1: Sieve Analysis for Fine Aggregate

Sieve No.	British Standard Sieve Sizes (mm)	Mass Retained (g)	Mass Passing (g)	Percentage Passing (%)
$\frac{1}{8}$	3.35		100	100
7	2.36	1.44	98.56	98.56
10	2	1.31	97.25	97.25
14	1.18	7.3	89.95	89.95
25	0.6	9.8	80.15	80.15
36	0.425	26.56	53.59	53.59
52	0.3	27.75	25.84	25.84
72	0.212	14.64	11.2	11.2
100	0.15	5.54	5.66	5.66
200	0.075	3.16	2.5	2.5

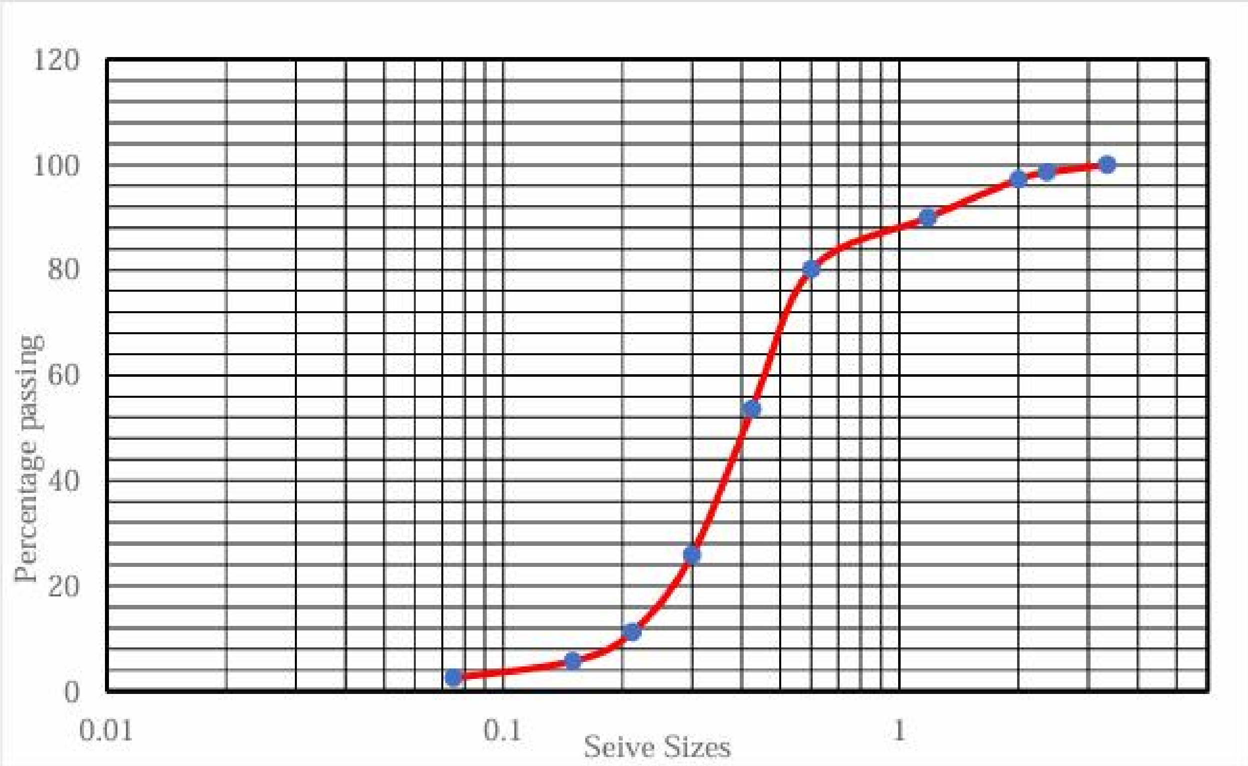


Figure 4.1: Grading Curve for Fine Aggregate

Table 4.2: Sieve Analysis for Coarse Aggregate

Sieve size(mm)	Retained mass (Kg)	(%) Mass Retained	Mass Passing (Kg)	Cumulative Mass Passing (%)
37.5	0.000	0	7.00	100
19	1.603	23	5.397	77
13.26	3.192	45	2.205	32
10	1.162	16.8	1.043	15.2
8	0.574	8.4	0.469	6.8
5	0.371	5.3	0.098	1.5

Sieve size(mm)	Retained mass (Kg)	(%) Mass Retained	Mass Passing (Kg)	Cumulative Mass Passing (%)
Pan	0.098	1.5	0	0
Total	7.00	100		

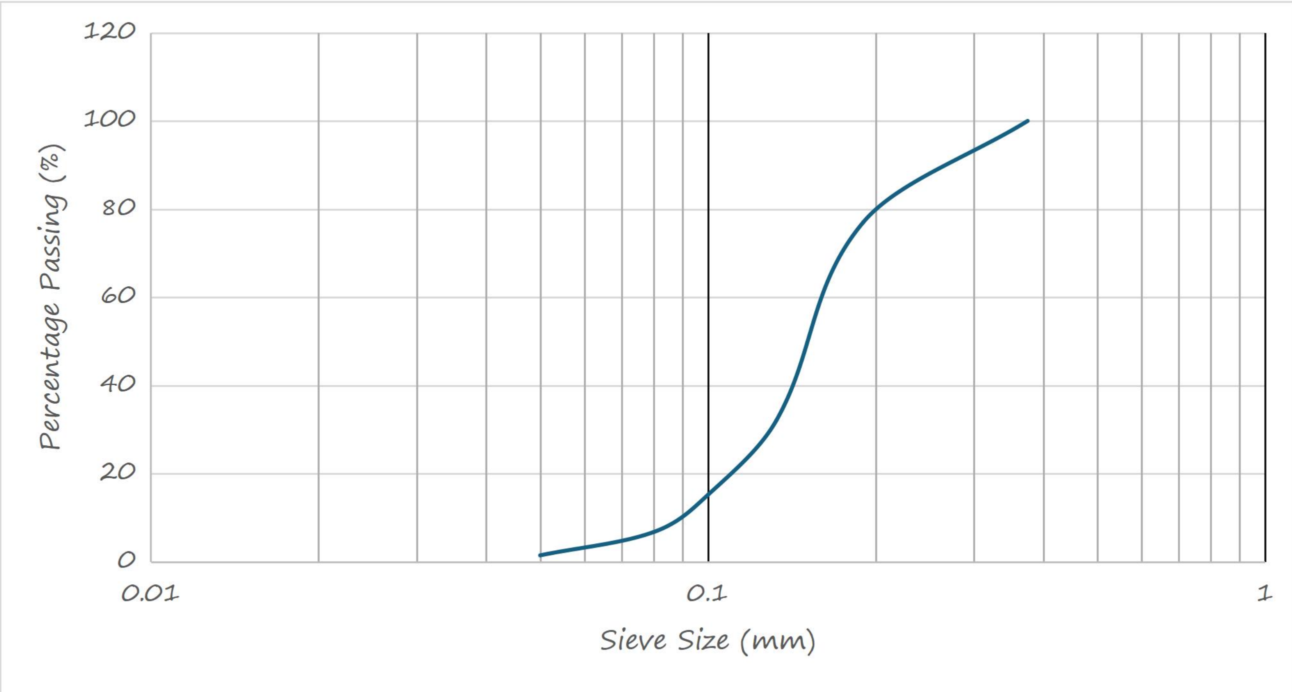


Figure 4.2: Grading Curve for Coarse Aggregate

Table 4.3: Sieve Analysis for Wood Ash

Sieve size(mm)	Retained mass (Kg)	% Mass Retained	Mass Passing (Kg)	Cumulative Mass Passing
2.36	0.00	0.00	100	100
2.00	0.00	0.00	100	100
1.18	2.40	2.40	97.60	97.75

Sieve size(mm)	Retained mass (Kg)	% Mass Retained	Mass Passing (Kg)	Cumulative Mass Passing
0.600	10.70	10.70	86.90	87.10
0.425	3.300	3.00	83.90	84.40
0.300	11.60	11.60	72.30	72.50
0.212	20.50	20.50	51.80	52.00
0.150	10.40	10.40	41.40	41.80
0.075	2.10	2.10	39.30	39.60

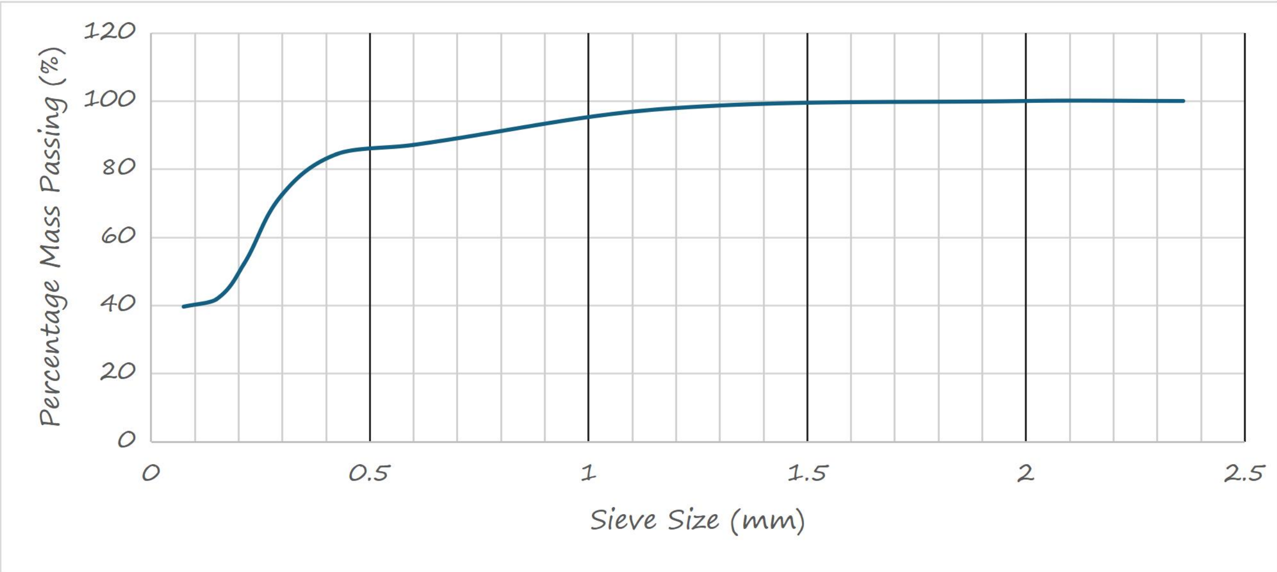


Figure 4.3: Sieve Analysis Grading Curve for wood ash

4.1.3 Slump Test

Table 4.4 presents the results of the slump test conducted on concrete mixes with varying levels of wood ash replacement. The slump values, measured in millimeters, indicate the relative workability of the mixes. As shown, increasing the percentage of wood ash substitution leads to a progressive reduction in slump, highlighting the impact of higher replacement levels on the ease of placement and compaction of fresh concrete.

Table 4.4: Slump Test

Percentage Replacement	Slump Value (mm)
0	30
5	25
10	10
15	4
20	0

4.1.4 Compressive Strength

Compressive strength as compared to conventional concrete was observed at 5% replacement of cement with wood ash in the concrete. There was a decrease in compressive strength at 10% replacement and below compared with the control concrete. 5% replacement had a closer compressive strength (31.86N/$mm2$) to the control concrete (32.51N/$mm2$) at 28 days than other replacements below 5%. The compressive strength at 5% replacement with wood ash is the highest for all percentage replacements with wood ash. The use of wood ash resulted in an increase in compressive strength, although it did not reach the levels observed in the control specimens. The best results were achieved with a 5% replacement. Table 4.6

highlights the age-related strength progression, the values still fall within acceptable limits, as specified in BS 8500-2:2015 (Concrete – Complementary British Standard to BS EN 206 – Part 2: Specification for Constituent Materials and Concrete).

Table 4.5: Compressive Strength of Concrete

Mix type	**Weight (kg)**		**Density (kg/$m3$)**		**Compressive strength (N/$mm2$)**		**Average Compressive strength (N/$mm2$)**	
	7 days	**28 days**	**7 days**	**28 days**	**7 days**	**28 days**	**7 days**	**28 days**
M0	2.45 2.50 2.37	2.61 2.63 2.64	2500 2550 2360	2655 2670 2690	18.90 18.95 19.00	30.00 32.53 35.00	18.95	32.51
M1	2.55 2.67 2.60	2.63 2.62 2.95	2550 2670 2600	2790 2620 2950	15.00 18.00 20.55	25.00 30.00 40.58	17.85	32.49
M2	2.51 2.44 2.45	2.55 2.73 2.52	2510 2440 2510	2683 2752 2520	15.00 18.00 18.24	28.5 31.11 33.73	17.08	31.11
M3	2.51 2.45	2.51 2.45	2620 2430	2770 2690	15.00 17.5	25.00 32.00	16.96	30.16

Mix type	Weight (kg)		Density (kg/$m3$)		Compressive strength (N/$mm2$)		Average Compressive strength (N/$mm2$)	
	2.52	2.52	2500	2630	18.38	34.83		
M4	2.55 2.41 2.47	2.79 2.75 2.70	2550 2410 2430	2640 2550 2700	15.00 17.00 17.29	28.50 31.00 31.16	16.43	30.12

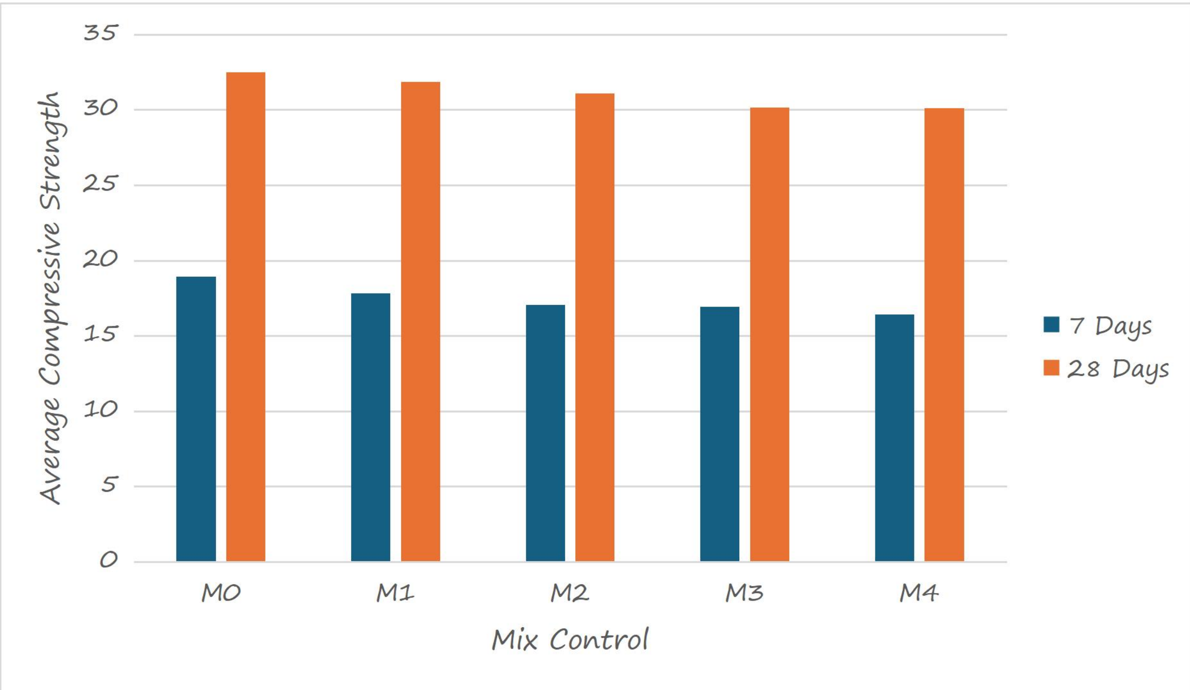


Figure 4.4: Compressive Strength of Concrete

4.4 Water Absorption Test

The water absorption test results showed varying permeability in concrete samples with different replacement percentages. The 8% replacement had moderate absorption at 8.00%, while the 5% replacement recorded 6.21%, both indicating adequate quality per BS 1881-122:2011. The 10% and 15% replacements demonstrated low absorption at 5.98% and 2.99%, respectively, reflecting good quality and durability, aligned with NIS 2007 standards. The 20% replacement maintained low absorption at 1.25%, further confirming good quality.

Table 4.6: Water Absorption

% Replacement	Dry Weight, W_1 (kg)	Saturated Weight, W_2 (kg)	Water Absorption (%)	Average Water Absorption (%)	Classification	Remarks
0%	2.473	2.571	3.90	8.00	Moderate absorption	Adequate quality with some resistance to freeze-thaw cycles and chemicals
	2.351	2.548	8.00			
	2.512	2.816	12.10			
5%	2.312	2.386	3.20	6.21	Moderate absorption	Adequate quality with some resistance to freeze-thaw cycles and chemicals
	2.288	2.336	2.10			
	2.395	2.417	0.92			
10%	2.256	2.318	2.75	3.50	Low absorption	Indicates excellent durability and

	2.235	2.339	4.65		(Good quality)	strong resistance to environmental factors
	2.254	2.324	3.11			
15%	2.212	2.276	2.89	2.99	Low absorption (Good quality)	Indicates excellent durability and strong resistance to environmental factors
	2.186	2.251	2.97			
	2.154	2.221	3.11			
20%	1.969	2.018	2.49	2.77	Low absorption (Good quality)	Indicates excellent durability and strong resistance to environmental factors
	2.128	2.189	2.87			
	1.897	1.953	2.95			

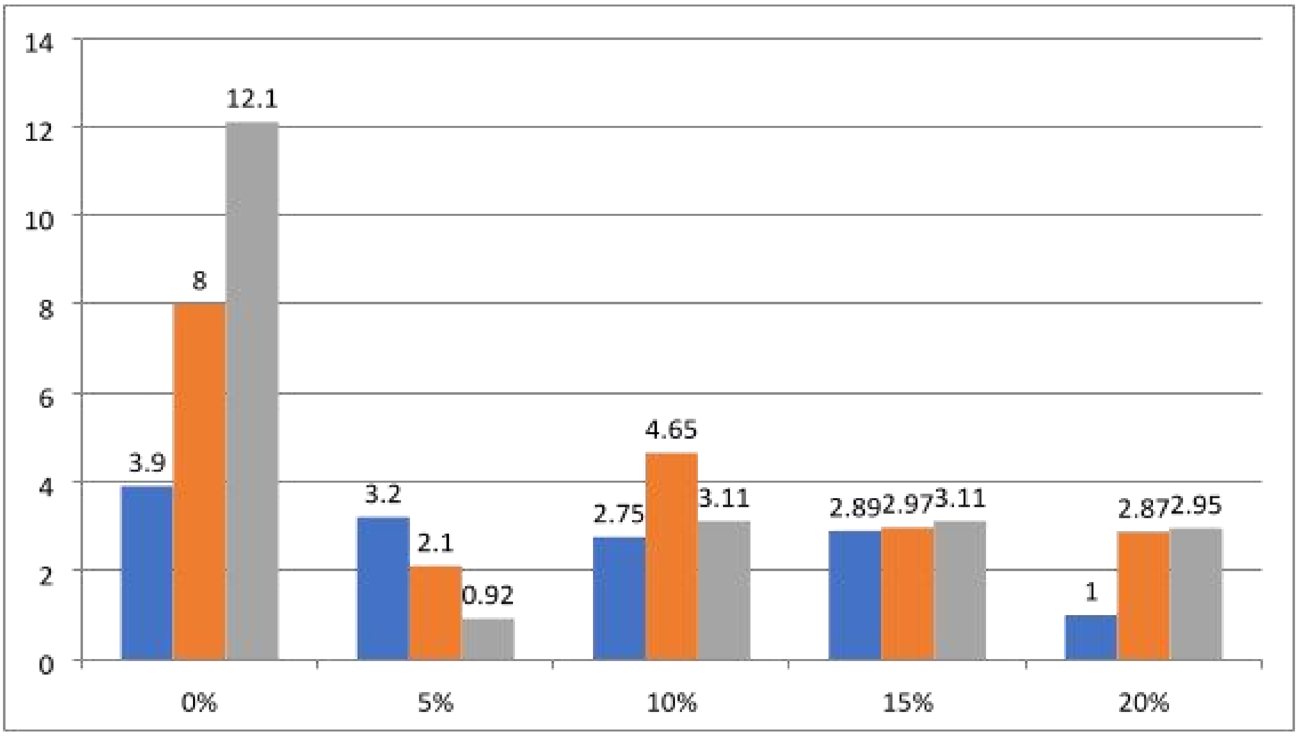


Figure 4.5: Water Absorption Curve

4.2 Discussion of Result

4.2.1 Analysis of Aggregate Properties and Concrete Performance

4.2.1 Sieve Analysis of Aggregates

The grading of both fine and coarse aggregates fell within the permissible limits, confirming their suitability for concrete production. Well-graded aggregates promote efficient packing, minimize voids, and reduce the quantity of cement paste required for binding. This ensured that the base materials used in this study were reliable and that the observed effects on workability and strength could be attributed primarily to the inclusion of wood ash rather than poor aggregate quality.

4.2.2 Slump Test

The slump values reduced steadily with higher wood ash content. The control mix had the highest slump, while the 20% replacement mix was unworkable. The reduction in workability is linked to the physical characteristics of wood ash. Compared to cement, the ash particles are finer, more porous, and irregular in shape. These features increase the water absorbed by the ash, leaving less free water available to lubricate the mix. The irregular particle shape also increases internal friction, which stiffens the mixture.

Although reduced workability is undesirable in conventional reinforced concrete, it may be useful in applications like block or kerb production, where stiffer mixes retain shape better after demolding. In structural works, however, chemical admixtures such as superplasticizers would be necessary to offset the loss of slump at higher replacement levels.

4.2.3 Compressive Strength

The compressive strength results showed that all mixes gained strength with curing age, which is expected as hydration products develop over time. The 5% replacement mix achieved a 28-day strength almost equal to that of the control (32.49 N/mm² compared to 32.51 N/mm²). This indicates that at low levels, wood ash can effectively replace cement without compromising strength. The fine ash particles likely acted as fillers, reducing porosity and enhancing density. Some pozzolanic reaction may also have occurred, where reactive silica in the ash combined with calcium hydroxide from cement hydration to produce additional calcium silicate hydrate.

At replacement levels beyond 10%, compressive strength reduced significantly. The decline can be explained by the lower cement content available to form hydration products and the limited pozzolanic activity of untreated wood ash. At 20% replacement, strength dropped to 30.12 N/mm², which, although still within acceptable limits for some non-structural applications, is inadequate for structural concrete. This trend supports findings from previous research, which identified low to moderate replacement levels as optimal.

Overall, the results demonstrate that wood ash has potential as a supplementary cementitious material when used in small quantities. Workability decreases with increasing ash content, but at 5% replacement, concrete strength is maintained at levels comparable to the control. Beyond 10%

replacement, strength losses become significant, indicating that higher substitution levels are unsuitable for structural applications. These findings suggest that wood ash can contribute to sustainable construction practices by reducing cement consumption and recycling industrial waste, provided replacement levels are kept within safe limits.

4.2.2 Implications for WA Usage

The findings from this study suggest that wood ash can be safely incorporated into concrete at low replacement levels. A substitution of about 5% provided compressive strength values that were practically identical to the control, making it suitable for structural applications such as beams, slabs, and columns. At higher replacement levels, strength decreased noticeably, which indicates that such mixes are more appropriate for non-structural or lightly loaded elements like paving blocks, kerbs, and partition walls.

For structural purposes, the performance of wood-ash-blended concrete could be further improved by adopting measures such as pre-treating the ash, using finer grinding, or incorporating chemical admixtures to counteract the loss in workability and strength. Although higher replacement levels are not advisable for load-bearing members, they still offer value in applications where strength requirements are moderate.

From an economic standpoint, the use of wood ash reduces the volume of cement required in a mix, which directly lowers construction costs. Since wood ash is often locally available at little or no cost, it provides an affordable alternative material. This makes it a promising option for non-structural works and for housing projects where affordability and sustainability are major considerations.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This study investigated the effect of partially replacing cement with wood ash on the properties of grade 25 concrete. The experimental program consisted of sieve analysis on aggregates, slump test on fresh concrete, and compressive strength testing of hardened cubes cured for 7, 14, and 28 days. From the results obtained, several important conclusions were reached.

5.1.1 Sieve Analysis Findings

The sieve analysis confirmed that both fine and coarse aggregates satisfied standard specifications for concrete production. This indicates that the aggregates used were suitable for structural applications. Wood ash, however, was found to be finer and more irregular than cement. Its particle characteristics, particularly its porosity and surface area, contributed to higher water demand and lower workability of the mixes when used in larger proportions.

5.1.2 Slump Test Observations

The slump test demonstrated a progressive reduction in workability with increasing wood ash content. The control mix at 0% replacement recorded a slump value of 30 mm, which reduced gradually with higher levels of replacement until the mix containing 20% wood ash showed 0 mm slump. This result highlights that wood ash reduces the ease of placement and compaction of fresh concrete, a challenge linked to its fineness and water absorption capacity. In practical terms, mixes containing high amounts of wood ash would require chemical admixtures or additional measures to restore workability.

5.1.3 Compressive Strength Findings

The compressive strength results revealed that low levels of wood ash incorporation had little to no negative effect on strength development. At 5% replacement, the strength achieved after 28 days (32.49 N/mm^2) was nearly identical to the control (32.51 N/mm^2). This demonstrates that small quantities of wood ash can be used as a supplementary cementitious material without compromising strength. However, as the replacement level increased beyond 5%, there was a consistent decline in strength. The mix with 20% wood ash produced the lowest strength value of 30.12 N/mm^2, which, although still acceptable for grade 25 concrete, indicates a significant dilution of the cementitious content. The reduction is attributed to the limited availability of calcium silicate hydrate gel when cement is partially replaced by higher volumes of ash.

5.1.4 Environmental Impacts

In addition to these technical outcomes, the environmental implications of this study are significant. Cement production is a major contributor to global carbon dioxide emissions, and its partial substitution reduces the overall carbon footprint of concrete. At the same time, wood ash is often disposed of as waste, posing environmental management challenges. Incorporating wood ash into concrete therefore supports sustainable construction by turning waste into a useful resource and reducing dependence on cement.

Overall, the study demonstrates that wood ash can effectively replace cement in concrete up to a maximum of 5% in structural applications, where both strength and workability must be preserved. For higher replacement levels, the strength loss becomes more pronounced, making such mixes more suitable for non-structural elements.

5.2 Recommendations

5.2.1 Structural Applications

For structural elements such as beams, slabs, and columns, it is recommended that the proportion of cement replaced with wood ash should not exceed 5%**.** This limit ensures that the compressive strength of the concrete remains within the acceptable range required for load-bearing capacity, while also maintaining adequate workability for proper placement and compaction. Exceeding this threshold may compromise structural performance, but at the 5% level, wood ash can be safely utilized as a partial replacement, contributing to sustainability without sacrificing durability or construction quality.

5.2.2 Non-Structural Applications

For non-structural applications such as paving blocks, kerbs, and partition walls, it is recommended that wood ash replacement levels of up to 20% may be considered. These elements are not highly load-bearing, which means the slight reduction in compressive strength does not compromise their performance. At the same time, the higher substitution level offers significant sustainability benefits, including reduced cement consumption and lower environmental impact. Therefore, the balance between acceptable strength loss and enhanced sustainability justifies the use of wood ash at this proportion in non-structural components.

5.2.3 Workability Improvements

Since workability decreases with higher wood ash content, the use of chemical admixtures such as superplasticizers is recommended to improve slump without increasing the water–cement ratio. Careful monitoring of water content is also essential to prevent segregation, bleeding, or shrinkage cracking.

5.2.4 Quality Control of Wood Ash

The chemical composition of wood ash varies with the type of wood, combustion temperature, and collection method. It is therefore advisable to conduct characterization tests (chemical analysis, particle size distribution, and loss on ignition) before use in concrete. Pre-treatment methods such as sieving, washing, or controlled calcination should also be carried out to eliminate impurities such as unburnt carbon and soluble salts that may compromise concrete performance.

5.2.5 Environmental and Economic Considerations

The reuse of wood ash in concrete production should be promoted, as it reduces the volume of waste directed to landfills, lowers cement demand, and minimizes greenhouse gas emissions. In regions with abundant sawmill and wood-processing activities, this practice can also result in significant cost savings while supporting sustainable construction practices.

5.2.6 Areas for Further Research

Future research should extend beyond compressive strength to include durability aspects such as resistance to sulphate and chloride attack, carbonation, shrinkage, and long-term creep. Microstructural studies using techniques like scanning electron microscopy (SEM) and X-ray diffraction (XRD) are recommended to better understand the hydration mechanisms of cement–wood ash blends. Additional work should explore hybrid replacements of wood ash with other supplementary cementitious materials, such as fly ash, silica fume, or rice husk ash. Finally, field-scale trials and life-cycle assessments are necessary to validate laboratory findings and to provide practical evidence of the environmental and economic advantages of wood ash concrete in construction projects.

REFERENCES

Abdulkareem, O.A.; Matthews, J.C.; Bakri, A.M.M.A. Strength and Porosity Characterizations of Blended Biomass Wood Ash-Fly Ash-Based Geopolymer Mortar. AIP Conf. Proc. 2018, 2045, 020096.

Abdullahi, M. Characteristics of Wood ASH/OPC Concrete. Leonardo Electron. J. Pract. Technol. 2006, 8, 9–16. 30. Rajamma, R.; Ball, R.J.; Tarelho, L.A.C.; Allen, G.C.; Labrincha, J.A.; Ferreira, V.M. Characterisation and Use of Biomass Fly Ash in Cement-Based Materials. J. Hazard Mater. 2009, 172, 1049–1060.

Amaral, R.C.; Rohden, A.B.; Garcez, M.R.; Andrade, J.J. de O. Reuse of Wood Ash from Biomass Combustion in Non-structural Concrete: Mechanical Properties, Durability, and Eco-efficiency. J. Mater. Cycles Waste Manag. Vol. 2022, 24, 2439–2454.

ASTM C618-15; Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. ASTM: West Conshohocken, PA, USA, 2015.

Bakhoum, E.S.; Amir, A.; Osama, F.; Adel, M. Prediction Model for the Compressive Strength of Green Concrete Using Cement Kiln Dust and Fly Ash. Sci. Rep. 2023, 13, 1864.

Bariˇcevi´c, A.; Carevi´c, I.; Bajto, J.Š.; Štirmer, N.; Bezinovi´c, M.; Kristovi´c, K. Potential of UsingWood Biomass Ash in Low-Strength Composites. Materials 2021, 14, 1250.

Berra, M.; Mangialardi, T.; Paolini, A.E. Reuse of Woody Biomass Fly Ash in Cement-Based Materials. Constr. Build. Mater. 2015, 76, 286–296.

Boussaa, N.; Kheloui, F.; Chelouah, N. Mechanical, Thermal and Durability Investigation of Compressed Earth Bricks Stabilized with Wood Biomass Ash. Constr. Build. Mater. 2023, 364, 129874.

Castrillón, J.J.; Gil, H. Mechanical Properties of Mortars Modified with Wood Waste Ash. J. Indian Acad. Wood Sci. 2020, 17, 90–99.

Carevi´c, I.; Bariˇcevi´c, A.; Štirmer, N.; Šantek Bajto, J. Correlation between Physical and Chemical Properties of Wood Biomass Ash and Cement Composites Performances. Constr. Build. Mater. 2020, 256, 119450.

Carevi´c, I.; Serdar, M.; Štirmer, N.; Ukrainczyk, N. Preliminary Screening of Wood Biomass Ashes for Partial Resources Replacements in Cementitious Materials. J. Clean. Prod. 2019, 229, 1045–1064.

Celik, I.B. The Effects of Particle Size Distribution and Surface Area upon Cement Strength Development. Powder Technol. 2009, 188, 272–276.

Cheah, C.B.; Part, W.K.; Ramli, M. The Long-Term Engineering Properties of Cementless Building Block Work Containing Large Volume of Wood Ash and Coal Fly Ash. Constr. Build. Mater. 2017, 143, 522–536.

Cheah, C.B.; Ramli, M. The Implementation of Wood Waste Ash as a Partial Cement Replacement Material in the Production of Structural Grade Concrete and Mortar: An Overview. Resour. Conserv. Recycle. 2011, 55, 669–685.

Chowdhury, S.; Maniar, A.; Suganya, O.M. Strength Development in Concrete with Wood Ash Blended Cement and Use of Soft Computing Models to Predict Strength Parameters. J. Adv. Res. 2015, 6, 907–913.

Chowdhury, S.; Mishra, M.; Suganya, O. The Incorporation of Wood Waste Ash as a Partial Cement Replacement Material for Making Structural Grade Concrete: An Overview. Ain. Shams Eng. J. 2015, 6, 429–437.

De Brito, J.; Kurda, R. The Past and Future of Sustainable Concrete: A Critical Review and New Strategies on Cement-Based Materials. J. Clean. Prod. 2021, 281, 123558.

EN 450-1; Fly Ash for Concrete—Part 1: Definition, Specifications and Conformity Criteria. Slovenski Inštitut za Standardizacijo: Ljubljana, Slovenia, 2012; 50.

Ellinwa AU, Ejeh SP, Akapabio IO. Using metakaolin to improve sawdust ash concrete. Concrete, International Journal of Innovative Science, Engineering & Technology, Vol. 1 Issue 10, December 2014

Etiégni, L.; Campbell, A.G. Physical and Chemical Characteristics of Wood Ash. Bioresour. Technol. 1991, 37, 173–178.

Garcia, M.D.L.; Sousa-Coutinho, J. Strength and Durability of Cement with Forest Waste Bottom Ash. Constr. Build. Mater. 2013, 41, 897–910.

Gerges, N.; Issa, C.A.; Antoun, M.; Sleiman, E.; Hallal, F.; Shamoun, P.; Hayek, J. Eco-Friendly Mortar: Optimum Combination of Wood Ash, Crumb Rubber, and Fine Crushed Glass. Case Stud. Constr. Mater. 2021, 15, e00588.

Global Cement and Concrete Association. Available online: Https://Gccassociation.Org (accessed on 8 June 2022).

Hamid, Z.; Rafiq, S. An Experimental Study on Behavior of Wood Ash in Concrete as Partial Replacement of Cement. Mater. Today Proc. 2021, 46, 3426–3429.

Harja, M.; Gencel, O.; Sarı, A.; Sutcu, M.; Erdogmus, E.; Hekimoglu, G. Production and Characterization of Natural Clay-Free Green Building Brick Materials Using Water Treatment Sludge and Oak Wood Ash. Arch. Civ. Mech. Eng. 2022, 22, 79

Hills, C.D.; Tripathi, N.; Singh, R.S.; Carey, P.J.; Lowry, F. Valorisation of Agricultural Biomass-Ash with CO2. Sci. Rep. 2020, 10, 13801.

James, A.K.; Thring, R.W.; Helle, S.; Ghuman, H.S. Ash Management Review-Applications of Biomass Bottom Ash. Energy 2012, 5, 3856–3873.

J Werther, M Saenger, E-U Hartge, T Ogada, Z Siagi, Combustion of agricultural residues, Journal of Progress in energy and combustion science, 2000.

Khan MI, Lynsdale CJ. Strength, permeability, and carbonation of high-performance concrete, Journal of Cement Concrete Residue 32:123–31.

Kannan, V.; Raja Priya, P. Evaluation of the Permeability of High Strength Concrete Using Metakaolin and Wood Ash as Partial Replacement for Cement. SN Appl. Sci. 2021,

Lazik, P.-R.; Bošnjak, J.; Cetin, E.; Kücük, A. Application of Wood Ash as a Substitute For Fly Ash And Investigation of Concrete Properties. Otto-Graf-J. 2020, 19, 103–118.

Loo SV, Koppejan J. Handbook of Biomass Combustion and Co firing. The Netherlands: Twente University Press.

Maresca, A.; Hansen, M.; Ingerslev, M.; Astrup, T.F. Column Leaching from a Danish Forest Soil Amended withWood Ashes: Fate of Major and Trace Elements. Biomass Bioenergy 2018, 109, 91–99.

Monteiro, P.J.M.; Miller, S.A.; Horvarth, A. Towards Sustainable Concrete. Nat. Mater. 2017, 16, 698–699.

Naik TR, Kraus RN, Siddique R. Demonstration of manufacturing technology for concrete and CLSM utilizing wood ash from Wisconsin, Wisconsin Department of Natural Resources (Madison, WI) for project #1-06 UWM report no. CBU-2002-30, Center for By- products Utilization, Department of Civil Engineering and Mechanics, University of Wisconsin-Milwaukee, Milwauke; 2002

Omran, A.; Soliman, N.; Xie, A.; Davidenko, T.; Tagnit-Hamou, A. Field Trials with Concrete Incorporating Biomass-Fly Ash. Constr. Build. Mater. 2018, 186, 660–669.

Ottosen, L.M.; Hansen, E.Ø.; Jensen, P.E.; Kirkelund, G.M.; Golterman, P. Wood Ash Used as Partly Sand and/or Cement Replacement in Mortar. Int. J. Sustain. Dev. Plan. 2016, 11, 781–791.

Rajamma, R.; Senff, L.; Ribeiro, M.J.; Labrincha, J.A.; Ball, R.J.; Allen, G.C.; Ferreira, V.M. Biomass Fly Ash Effect on Fresh and Hardened State Properties of Cement Based Materials. Compos. B Eng. 2015, 77, 1–9.

Ramos, T.; Matos, A.M.; Sousa-Coutinho, J. Mortar with Wood Waste Ash: Mechanical Strength Carbonation Resistance and ASR Expansion. Constr. Build. Mater. 2013, 49, 343–351

S. Chowdhury, A. Maniar, O.M. Suganya, 2014, Journal of advanced research, "Strength development in concrete with wood ash blended cement and use of soft computing models to predict strength parameters"

Siddique, R. Utilization of Wood Ash in Concrete Manufacturing. Resour. Conserv. Recycl. 2012, 67, 27–33.

Teixeira, E.R.; Camões, A.; Branco, F.G. Valorisation of Wood Fly Ash on Concrete. Resour. Conserv. Recycl. 2019, 145, 292–310.

Sigvardsen, N.M.; Kirkelund, G.M.; Jensen, P.E.; Geiker, M.R.; Ottosen, L.M. Impact of Production Parameters on Physiochemical Characteristics of Wood Ash for Possible Utilisation in Cement-Based Materials. Resour. Conserv. Recycl. 2019, 145, 230–240.

Ukrainczyk, N.; Vrbos, N.; Koenders, E.A.B. Reuse of Woody Biomass Ash Waste in Cementitious Materials**.** Chem. Biochem. Eng. Q 2016, 30, 137–148.

Sigvardsen, N.M.; Ottosen, L.M. Characterization of Coal Bio Ash fromWood Pellets and Low-Alkali Coal Fly Ash and Use as Partial Cement Replacement in Mortar. Cem. Concr. Compos. 2019, 95, 25–32.

Teixeira, E.R.; Mateus, R.; Camões, A.F.; Bragança, L.; Branco, F.G. Comparative Environmental Life-Cycle Analysis of Concretes Using Biomass and Coal Fly Ashes as Partial Cement Replacement Material. J. Clean. Prod. 2016, 112, 2221–2230.

Thomas, B.S.; Yang, J.; Mo, K.H.; Abdalla, J.A.; Hawileh, R.A.; Ariyachandra, E. Biomass Ashes from Agricultural Wastes as Supplementary Cementitious Materials or Aggregate Replacement in Cement/Geopolymer Concrete: A Comprehensive Review. J. Build. Eng. 2021, 40, 102332

Tripathi, N.; Hills, C.D.; Singh, R.S.; Atkinson, C.J. Biomass Waste Utilisation in Low-Carbon Products: Harnessing a Major Potential Resource. NPJ Clim. Atmos. Sci. 2019, 2, 35.

Tripathi, N.; Hills, C.D.; Singh, R.S.; Singh, J.S. Offsetting Anthropogenic Carbon Emissions from Biomass Waste and Mineralized Carbon Dioxide. Sci. Rep. 2020, 10, 958.

Udoeyo, F.F.; Inyang, H.; David, Y.T.; Oparadu, E.E. Potential of WoodWaste Ash as an Additive in Concrete. J. Mater. Civ. Eng. 2006, 18, 605–611