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Effect of Wood Ash as Alternative Cementitious Material in Partial Replacement of Cement in Concrete Production

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Abstract:

The construction industry is under increasing pressure to reduce carbon emissions and explore sustainable building materials. This study investigates wood ash as sustainable cementitious material by partially replacing cement in concrete. Wood ash has the potential and pozzolanic properties that possibly can enhance concrete strength and performance. Concrete mix were prepared with wood ash replacement of cement, 0%, 5%, 10%, 15% and 20% using a concrete mix ratio was 1 : 1½ : 3 with 0.5 w/c., for curing period 7, 14, 21 and 28 days. Regression models and analysis were performed on the compressive and tensile tests results towards evaluating the significance of wood ash in concrete. The results of slump tests showed gradual decrease with increasing wood ash varying from 85mm (0% WA level) to 70mm at 20% WA level. Even though workability was decreasing it was found to be within standard for medium workability concrete (50 – 90mm). Compressive strength was maximum at 10% WA level (15.51N/mm^2) while control was 19.08N/mm^2 at 28 days. Similarly the split tensile strength was maximum at 10% (1.97 N/mm^2) compared with 2.08 N/mm^2 at 0% (control mix). The Regression model used was σ = a – b (% WA Level) for the curing periods where a and b are parameters, the analysis provides comparable results with observed laboratory results. The study concluded that, for optimal results, replacement levels of cements by wood ash should be limited to 10% and possibility higher WA content could be achieved by inclusion of plasticizer to improve workability

Keywords: *Wood ash, cementitious, compressive strength, tensile strength, concrete*

1.0 Introduction

Production of Ordinary Portland Cement (OPC) is responsible for approximately 7% of global carbon dioxide emissions (He *et al*, 2019). As the world moves towards sustainable construction practices, finding alternative materials to replace cement becomes essential (Chen *et al*, 2024). Cement consists of various chemical compounds, mainly tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), and tetracalcium aluminoferrite (C_4AF), which is available in most materials classified as pozzolana. Wood ash, generated from combustion of wood biomass, offers a promising solution due to its pozzolanic properties (Chen L et al, 2024). The most extensively used artificial material in the world, is concrete and its application in structures including building, However, when urbanization rates rise in emerging nations like Nigeria, the growing need for concrete exacerbates environmental problems Ohwo and Abotutu, 2015). Nigeria's building industry is expanding quickly to fulfill the country's expanding population's demands for housing and infrastructure, which is causing a high cement consumption and related environmental effects. Therefore, it is essential to identify locally accessible and sustainable cement substitutes like the wood-ash, in order to minimize the environmental issues associated with cement production (Siddique, 2012). Wood ash, a byproduct of biomass combustion in businesses like lumber processing, biomass power plants, and even home wood stoves, is one viable substitute material. The chemicals that give wood ash its cementitious qualities are mainly calcium oxide (CaO), silica (SiO_3), and potassium oxide (K_2O). Wood ash is a resource that can be used as an additional cementitious material (SCM) rather than being disposed of as waste and adding to environmental contamination. This strategy reduces waste and the environmental impact of cement production, which is in line with the objectives of sustainable development. Incorporating wood ash into concrete production offers numerous environmental benefits namely:

(i) Reduction of cement consumption (i.e., sustainability

(ii) Utilization of local resources (Udoeyo, 2006)

The purpose of this study is to investigate the use of wood ash in concrete as partial substitute for cement, with emphasis on the material's property, mechanical property, environmental benefits, and suitability for application in concrete structures. The ultimate purpose includes evaluating wood ash cementitious, concrete's compressive strength, workability, and durability.

Numerous studies have explored the use of wood ash in concrete. For instance Torgal and Jalali (2011) noted enhancements in durability and resistance to environmental factors with wood ash incorporation. Ercan et al (2023) observed that depending on chemical composition of wood ash, the strength and durability properties of concrete might be slightly improved by utilizing wood ash as partial replacement for cement with an optimal level of 10-20%. Udoeyo et al (2009) observed that compressive and flexural strengths of wood waste ash ranged from 12.83N/mm^2 to 28.66N/mm^2 and 3.65N/mm^2 to 5.57N/mm^2 respectively with least values obtained at 30% replacement level, and compared with the control (0% WWA) the strengths were between 62 and 91% and 65 and 95% respectively, thus expressing usefulness in concrete. Reactivity of wood ash is primarily attributed to its silica content, which reacts with calcium hydroxide produced during cement hydration. Studies have shown that wood ash can improve the compressive strength and durability of concrete when used within optimal limits. Wood ash is composed of various inorganic minerals, including silica, alumina, and iron oxide, which contribute to its pozzolanic activity (Etiegni and Canpbell, 1991). The composition of wood ash varies significantly depending on the type of wood and combustion conditions (Abdullahi, 2006)

Typical components include calcium oxide, potassium oxide, magnesium oxide, and phosphorus pentoxide, making it a potential candidate for enhancing concrete properties.

Table 1: Chemical Composition of Wood ash from various Species of Timber

Biomass Group	SiO_2	CaO	K_2O	P_2O_5	Al_2O_3	MgO	Fe_2O_3	SO_3	Na_2O	TiO_2
Bitch hark	4.38	69.06	8.99	4.13	0.55	5.92	2.24	2.75	1.85	0.13
Forest residue	20.65	47.55	10.23	5.05	2.99	7.20	1.42	2.91	1.60	0.40
Pine bark	9.20	56.83	7.78	5.02	7.20	6.19	2.79	2.83	1.97	0.19
Pine chips	68.18	7.89	4.51	1.56	7.04	2.43	5.45	1.19	1.20	0.55
Poplar	3.87	57.33	18.73	0.85	0.68	13.11	1.16	3.77	0.22	0.28
Poplar bark	1.86	77.31	8.93	2.48	0.62	2.36	0.74	0.74	4.84	0.12
Sawdust	26/17	44.11	10.83	2.27	4.53	5.34	1.82	2.05	2.48	0.40
Spruce bark	6.13	72.39	7.22	2.69	0.68	4.97	1.90	1.88	2.02	0.12
Spruce wood	49.30	17.2	9.6	1.90	9.40	1.10	8.30	2.60	0.50	0.10
Wood residue	53.15	11.66	4.85	1.37	12.64	3.06	6.24	1.99	4.47	0.57

2.0 Materials and Methods

In this study, five main materials were used for the concrete mixes, namely cement, wood ash, fine aggregate (sand), coarse aggregate (granite), and water. Each material played a specific role in the performance of the concrete, contributing to its mechanical properties, workability, and durability, the cement/wood ash are the cementitious binder materials of the aggregates with appropriate water cement ratio of 0.5. Cement consists of various chemical compounds, mainly tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), and tetracalcium aluminoferrite (C_4AF). Ordinary Portland Cement wass used as the control material, and the primary material being replaced by wood ash in various percentages 0%, 5%, 10%, 15%, and 20%., a concrete mix ratio of 1: 1½ :3 (cementitous: fine: coarse aggregate), was used and 0.5 w/c for medium workability concrete..

2.1: Concrete Constituent Materials

Wood ash is the powdery residue remaining after combustion of wood, and the ash is the non-gaseous, non-liquid residue after complete combustion, also the condition of combustion affect the composition and amount of the residue ash, therefore higher temperature will reduce the ash yield (Misra et al, 1993).

Table 2: **Chemical Composition of Wood Ash and Cement**

Element Oxides	Wood Ash Percentage by mass	Cement Percentage by mass	Percentage difference
SiO_2	48.96	18.6	62.01
CaO	11.59	66.33	-472.30
Al_2O_3	11.24	3.77	66.46
Na_2O	8.76	1.39	84.13
K_2O	5.42	0.46	91.51
MgO	5.05	2.13	57.82
Fe_2O_3	0.6	4.03	-571.67
Loss of Ignition (LOI)	8.75	3.29	62.40

Fine aggregate used in this study was river sand sourced locally from the Ogun River in Nigeria. The sand was clean and sharp to enable adequate bonding with the cementitious binder, as specified by concrete standards and essential for producing quality concrete. Preliminary tests on the aggregates such as particle size distribution and fineness modulus showed that the sand particles passed through a 2.36mm sieve but were retained on a 0.06mm sieve. This ensures that the sand is free from fine dust, clay, or organic impurities, which could negatively affect the strength and durability of the concrete. A fineness modulus (FM) was 3.0 and was considered optimal for high-strength concrete (HSC). This refers to the uniformity of particle sizes, and it ensures a balance between workability and strength in the concrete mix.

Coarse aggregate used was crushed granite randomly sourced from local quarries. Granite is widely used in construction due to its strength and durability. In this study, a 50/50 mix of 10mm and 12.5mm sized granite was used. The crushed granite was angular, providing excellent interlocking properties, which contribute to the concrete's overall strength. The smaller size (10-12.5mm) of the aggregates ensures better distribution within the concrete matrix, reducing voids and helping to achieve higher compressive strengths.

Water/Cement: 0.5 w/c was used for all mixes. The mix ratio for control was kept at **1:1.5:3** (Cement: Fine Aggregate: Coarse Aggregate**)**, which as recommended concrete mix ratio for general purpose construction. The mixing water was clean and potable.

2.2 Laboratory Experiments

Slump test was conducted immediately after mixing to assess the workability of the concrete, and consistency or fluidity of the concrete mix according to BS EN 12350-2:2019. Concrete cubes were cast and removed from the mold after 24 hours and placed in a curing tank filled with water. Curing was done for **7, 14, 21 and 28 days**, and the cubes were tested for compressive strength at each curing age (BS 1881-1_ 1970 – Method of Testing Concrete**.**

3.0. RESULTS AND DISCUSSION

This chapter contain details of experimental observations, discussion of results and analysis of results using regression model σ = a + b(% WA) at various tests days

3.1: Result of Slump Test using Wood ash in Concrete

The slump test was performed on fresh concrete before setting; it provides information on consistency and wetness of concrete, referred as workability. Concrete workability pay significant role on the property of hardened concrete, it define the ease with which freshly mixed concrete is placed, compacted and finished without segregation or loss of homogeneity.

Table 3. Slump Test Results with percentage replacement of wood ash

% Replacement	Value of slump(mm)	Degree of workability
0%	90	Medium
5%	85	Medium
10%	80	Medium
15%	75	Low to Medium
20%	70	Low

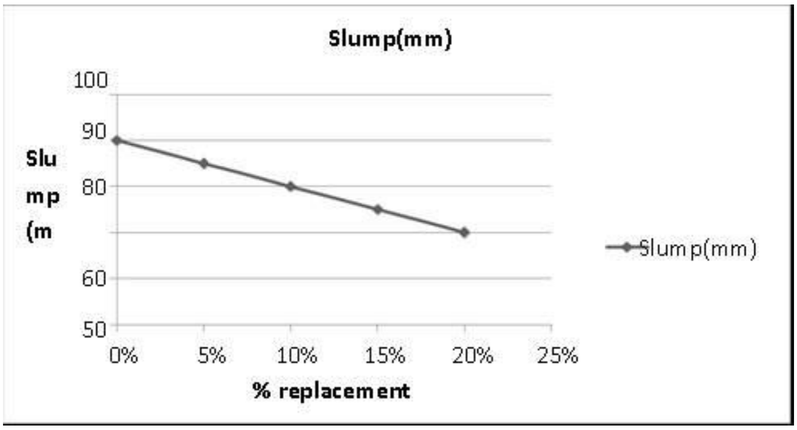

Figure 1: Slump value with % Wood ash content

Using wood ash as a partial replacement for cement in the concrete generally resulted in a reduction of slump, especially as the replacement percentage increased from 5% to 20%. This is due to the increased water demand associated with the finer particles and pozzolanic activity of wood ash. To maintain workability, it was necessary to adjust the water content of the mix design.

3.2: Compressive Strength of Wood ash-cement Concrete

Compressive strength is an important parameter in concrete design of structures and a mechanical property that describes ability of component to resist compressive force

. $\sigma = F/A$ (where F is ultimate (failure) load and A = cross sectional area)

In table 4 compressive strength results at 0% replacement was used as comparison standard, it was observed that inclusion of wood ash has significant effect on compressive strength, and it reduces as %WA replacement increases. 20% WA content had least compressive strength value for all tests periods, which shows that pozzolanic activity of WA-cement paste reduces with increase in wood ash content. Maximum compressive strength was attained at 10% WA and 28 days curing as 15.53 N/mm^2. And the control compressive strength max was 19.08 N/mm^2 at 28 days.

Table 4. Compressive Strength result of wood ash-cement Concrete

Curing days	0%	5%	10%	15%	20%
7days	18.58	13.96	13.21	13.16	13.04
14days	18.73	14.25	13.78	13.66	13.3
21days	18.93	14.43	14.55	13.96	13.45
28days	19.08	14.49	15.53	14.43	13.87

3.2.1: Regression Analysis of Compressive Strength

Effect of wood ash on the compressive strength of concrete is largely dependent on the replacement level of the wood ash Table 5 & 6). At lower replacement levels (5-10%), the wood ash contributed to comparable or even improved long-term compressive strength due to its pozzolanic activity. However, at higher replacement levels (above 15-20%), the compressive strength generally decreased, especially at early ages, due to the reduced cement content and slower pozzolanic reaction. Table 3.4, the predicted compressive strength results show that strength reduces with increase in WA content, and maximum at 28 days (16.53N/mm^2 at 28 days) with the control (0%) maximum value is 17.58N/mm^2 at 28 days

Table 5: Regression model equation at various curing days

Curing days	Model equation
7 days	σ = 16.766 – 0.2376 (% WA)
14 days	σ = 17.034 – 0.229 (% WA)
21 days	σ = 17.35 – 0.2286 (% WA)
28 days	σ = 17.576 – 0.2096 (% WA)

Table 6: Predicted Compressive Strength using Regression Analysis

Curing period	0 % WA N/mm^2	5 % WA N/mm^2	10 % WA N/mm^2	15 % WA N/mm^2	20 % WA N/mm^2
7 days	16.77	15.58	14.39	13.20	12.02
14 days	17.04	15.89	14.74	13.60	12.45
21 days	17.35	16.21	15.07	13.92	12.78
28 days	17.58	16.53	15.48	14.43	13.39

3.3: Split Tensile Strength of Concrete

Concrete has low tensile strength by formation; therefore the split tensile strength test provides a complementary data with the compressive strength to measure the bond strength in WA-cement concrete. ASTM C496-96 is the standard used to determine the splitting tensile strength on concrete test cylinders

Table 7 : Results of split tensile strength Tests

	Tensile strength N/mm^2				
Curing days	**0%**	**5%**	**10%**	**15%**	**20%**
7 days	1.83	1.78	1.8	1.77	**1.77**
14 days	1.9	1.78	1.81	1.75	**1.75**
21 days	1.95	1.85	1.88	1.85	**1.8**
28 days	**2.08**	**1.95**	**1.97**	**1.95**	**1.9**

Effect of wood ash on the tensile strength of concrete is generally similar to its effect on compressive strength, but the impact is more pronounced due to the lower inherent tensile strength of concrete. At lower to moderate replacement levels (5-10%), the tensile strength may be maintained or slightly improved in the long term due to the pozzolanic activity of the wood ash, which enhances the bond within the concrete matrix. However, at higher replacement levels (above 15-20%), the tensile strength is likely to decrease, especially at early ages, due to the dilution of cement content and the slower pozzolanic reaction

4.0: CONCLUSION AND RECOMMENDATION

4.1: Conclusion

This study confirms that wood ash can effectively serve as partial replacement of OPC in concrete production, particularly in Nigeria's rapidly growing construction sector. While lower percentages of wood ash enhance the mechanical properties of concrete, higher replacements may compromise strength. Thus, careful consideration of the replacement ratio is critical to optimizing both performance and sustainability.

The research contributes valuable data to the ongoing dialogue about eco-friendly construction materials and highlights the importance of leveraging local resources to address both environmental and infrastructural challenges. By incorporating wood ash, the construction industry can move towards a more sustainable future.

4.2: Recommendations

For optimal results, the replacement levels of cements by wood ash should be limited to 10% or carefully selected based on the desired balance between workability, early strength and long term strength. Incorporating chemical admixtures or plasticizers may help improve workability in mixes with higher wood ash content

References

Abdullahi, M. (2006). Characteristics of Wood Ash-OPC Concrete. Leonardo Electronic Journal of Practices and Technologies, Vol 8(7), Pp 9-16.**ISSN No 1583-1078**

Adewuyi A P and Ola B F (2005), Application of Water Works Sludge as Partial Replacement for Cement in Concrete Production Science Focus LAUTECH Journal, Vol 10(1) Pp 123-130. **ISSN No 1597-0000**

ASTM C496-96: Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens

ASTM C1362 – 09, (2014), Test Method for Flow of Freshly Mixed Hydraulic Cement Concrete. ASTM International

BS 1881-1: 1970, Method of Testing Concrete – Method of Mixing and Sampling Fresh Concrete in the laboratory

BS EN 12350-2:2019: Testing Fresh Concrete - Slump

Bui, D. D., Hu, J., & Stroeven, P. (2005). Particle Size Effect on Strength of Rice husk ash Blended Gap-graded Portland Cement Concrete. Cement and Concrete Composites, Vol 27(3), Vol 357-366. **ISSN No 0958-9465**

Cheah, C.B. and Ramli, M. (2011), Implementation of Wood Waste Ash as a Partial Cement Replacement Material in the Production of Structural Grade Concrete and Mortar: An Overview Resour. Conserv. Recycl. Vol 55, Pp 669–685. **ISSN No 0921-3449**

Chen L et al (2024) Conversion of Waste into Sustainable Construction Materials, A review of Recent Development and Prospects. Materials Today Sustainability, Vol 27. **ISSN No 2589-2347**

Ercan E T, Andreas L, Cwirzen A and Habermehi-Cwirzen (2023), Wood Ash as Sustainable Alternative Raw material for Production of Concrete. Journal of materials, Vol 16 (7) **ISSN No 0022-2453**

Etiégni, L.; Campbell, A.G. (1991) Physical and Chemical Characteristics of Wood Ash. Bioresour. Technol. Vol 37, Pp 173–178. **ISSN No 0960-8524**

Felekoglu,B. Turkel,S., and Baradan,B. (2007). Effect of Water/Cement ratio on the Fresh and Hardened Properties of Self-compacting Concrete. Building and Environment, Vol 42(4), Pp 1795-1802. **ISSN No 0360-1323**

He Z, Wang J, Mu M and Zhu X (2019), Comparison of CO_2 Emissions from OPC and Recycled Cement Production. Construction and Building Materials, Vol 211, Pp 965-973. **ISSN No 0950-0618**

Misra M K, Ragland K W and Baker A J (1993), Wood Ash Composition as a Function of Furnance Temperature. Journal of Biomass and Energy, Vol 4 (2), Pp 103-116. **ISSN No 0961-9534**

Ohwo O and Abotutu A (2015), Environmental Impact of Urbanization in Nigeria. British Journal of Applied Science and Technology, Vol 9 (3), Pp 212-221. **ISSN No 2231-0843**

Rachamalla S, Shaheen F and Palvadi S (2020), Partial Replacement of Cement with Wood Ash and Fly Ash in Pavement Quality Concrete. International Journal of Innovative Technology and Exploring Engineering, Vol 9 (5), Pp 1513-1515. **ISSN No 2278-3075 (online)**

Siddique, R. (2012), Utilization of Wood Ash in Concrete Manufacturing. Resour. Conserv. Recycl. Vol 67, Pp 27–33. **ISSN No 0921-3449**

Torgal F and Jalali S (2011), Compressive Strength and Durability Properties of Ceramic wastes Based Concrete. Materials and Structures, Vol 44 (1), Pp 155-167. **ISSN No 2716-8077**

Udoeyo, F.F.; Inyang, H.; David, Y.T.; Oparadu, E.E.(2006) Potential of Wood Waste Ash as an Additive in Concrete, J. Mater. Civ. Eng. Vol 18, Pp 605–611. **ISSN No 0899-1561**