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Validating The Effectiveness Of Local Firewood Ash As A Supplementary Cementitious Material In Concrete

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***Abstract*—Firewood ash (FWA) is the residue generated from combustion of firewood commonly used as fuel for cooking especially for public and community parties. FWA is a non-biodegradable material not environmentally safe for disposal in landfill. The physical and chemical properties of FWA and its influence as a supplementary cementitious material (SCM) in concrete were investigated for fresh and hardened concrete. The firewood residues from regular cooking combustion were subject to controlled combustion in an industrial oven at a temperature of 1000°C for 2 hours. The pH, specific gravity and specific surface area of FWA were 10.3, 2.25 and 10.7 m^2/g, respectively. The chemical composition of the FWA by x-ray fluorescence (XRF) analysis showed that combined silica, alumina and hematite (<10%) contents accounted for an average of 62.45% and CaO was greater than 10% for all the FWA samples. FWA was introduced as partial replacement for cement in the ratio 0% (control mixture) to 30% at an interval of 10% for concrete mix ratio 1:1.86:2.25 of water-cement ratio of 0.49 for a target compressive strength or 28 N/mm^2. The workability of the concrete mixtures, in terms of slump test, fell within the acceptable standard limits for all FWA contents except for the 30% FWA that would require super-plasticizer to be workable. The water absorption (< 10%) increased with the FWA contents and satisfied standard requirement for building and concrete works. The 28-day compressive and split tensile strengths showed that the permissible FWA content was 20%.**

***Keywords*—Blended cement concrete, firewood ash, supplementary cementitious materials, workability, waste management, additives, compressive strength, tensile strength, water absorption.**

I. Introduction

Wood ash is the residue generated due to combustion of wood and wood products (chips, saw dust, bark, etc.). It is the inorganic and organic residue remaining after the combustion of wood or unbleached wood fibre. Hardwoods usually produce more ash than softwoods and the bark and leaves generally produce more ash than the inner woody parts of the tree. Typical wood burnt for fuel at pulp and paper mills and wood products industries may consist of saw dust, wood chips, bark, and saw mill scraps, hard chips rejected from pulping, excess screenings such as sheaves and primary residuals without mixed secondary residuals [1-2]. On the average, the burning of wood results in about 6–10% ashes [3-5].

Firewoon ash (FWA) is a product of burning or gasifying wood and consists mainly of minerals that trees have absorbed over their lifetime. Pure wood without bark produces little ash compared to wood with bark, while whole trees with needles and leaves produce high ash level [6-7]. Wood ash is used as a feedstock for cement production and road base material in Europe [8]. In the 1990s, about 28% of the total wood ash produced in the US is being utilized [9]. Approximately 70% of the wood ash generated is land-filled, 20% is applied on land as a soil supplement, and the remaining 10% is used for miscellaneous applications [1-2] including construction materials, metal recovery, and pollution control.

Physical and chemical properties of wood ash are important in determining their beneficial uses. These properties are influenced by species of tree, tree growing regions and conditions, method and manner of combustion including temperature, other fuel used with wood fuel, and method of wood ash collection [11]. Agriculturally, wood ash has been found more beneficial in raising the pH level and other nutrients of soil compared to lime. The calcium carbonate equivalent (CCE) of different wood ash may vary considerably from 25% to 60%. However, special care is required in this process to percolation into the groundwater or discharge onto the surface water which may lead to significant pollution [1,8].

Applicability of wood ash as a soil supplement is becoming more limited due to the presence of heavy metals and high alkalinity, as well as reduced availability of land for application. Due to these reasons, many attempts are being made to develop high-volume use technologies for wood ash, especially for use in construction materials [6].

Firewood waste ash consists of highly fine particulate matters, which can be easily rendered airborne by winds that may result in subsequent problems, namely, respiratory health problems to residents dwelling near the disposal site of the ash material. In addition, contamination of groundwater resources is also inevitable from leaching of heavy metal contents of FWA or by seepage of rain water [9]. Hence, disposal of wood waste ash by means of land-filling require a properly engineered land fill which have implications in terms of the cost of disposal.

The construction industry is a vast consumer of natural resources and among the largest greenhouse gases emission sources, which makes it one of the major threats to non-renewable natural resources. The integrated waste management strategy demands for reduction, recycling and reuse of wastes for a sustainable and cleaner environment. Recycling and reuse of wastes have found tremendous application in building and construction materials. Similar to other Class C and Class F fly ash from industrial combustion of coals, and incineration of agricultural wastes, industrial waste and sewage sludge [10-11]; wood ash has been found to be useful as a cement-based construction materials as a feedstock in the manufacture of Portland cement [1].

The unprecedented explosion of infrastructure development in the construction industry has placed a huge demand for cement which is the major constituent of concrete which account for over 75% of constructed infrastructure worldwide. The production of cement involves an intensive use of raw material (limestone) and energy, and the process releases about two-thirds of cement quantity as carbon dioxide into the atmosphere. The increased demand of cement implies a higher rate of environmental deterioration due to the limestone extraction activities, a higher requirement of fossil fuels and higher rate of green house gas discharge [16-17].

In the past two decades, an extensive research has been performed to investigate the feasibility of the use of wood ash as a partial replacement material for the energy intensive process of hydraulic cement for concrete production [4, 13, 18-20]. The tests showed promising results in that wood waste ash can suitably used as constituent material in during the production of structural grade concrete with acceptable mechanical and durability properties. However, the suitability of wood ash as a supplementary cementitious material (SCM) in concrete is a function of its physical and chemical properties which depend on the species and cleanliness of the fuel wood, and the collection location, thermodynamics of the combustion systems, combustion temperature, efficiency of the boiler, and supplementary fuels used [9,13-15].

Since wood ash composition can be highly variable depending on geographical location and industrial processes, the primary purpose of this study was to investigate the feasibility of firewood ash (FWA) from the residue of burnt or gasified firewood from cooking activities as partial replacement for cement among low-medium income earners in Botswana. This would play a three-fold role of waste management, environmental protection, saving of cement cost via economic and technical reuse of FWA as blended cement in concrete. The physical and chemical properties of FWA were reported, and the influence of varying FWA contents on the properties fresh and hardened concrete was presented.

II. Description of the Study Area

In Botswana, especially rural areas firewood is the most common sources of energy. Batswana use firewood as fuel for communal cookings which produce vast amounts of wood ash every weekend during social and cultural events including weddings, funerals, etc. The types of firewoods permitted for use as fuel or energy in Botswana are dead and dry trees that cannot absorb CO_2 and release O_2. The Botswana Forestry Acts state that "*no person shall in a forest reserve fell, cut, take, work, burn, injure or remove any forest produce*".

The massive increase in the population of Botswana has led to the increase in the demand for concrete which is needed for infrastructure development and building of personal houses. The estimated population of Botswana from the 2022 Population and Housing Census is 2,346,179 as compared to 2,024,904 enumerated in the 2011 Population and Housing Census (Statistics Botswana, 2022).The manufacture of cement releases greenhouse gases like CO_2 to the atmosphere hence contributing to global warming rigorously. It furthermore leads to the depletion of natural resources like limestone. The problem of land degradation due to improper wood ash disposal is an already existing problem. Landfilling is becoming very restrictive due to shrinking landfill space and strict environmental regulations.

FWA is readily available as many people in Botswana villages rely on firewood for energy especially for cooking during social and cultural events. Massive quantities of FWA generated at different locations in the rural and semi-urban centres in Botswana end in dumpsites where it is blown into the air or washed off onto land thereby polluting the air, soil, and groundwater. Fig. 1 shows typical firewood before and after combustion.

III. Experimental Programme

A. *Materials*

Grade 52.5 ordinary Portland cement was used in this study. Coarse aggregate was crushed granite of maximum nominal size of 19 mm. Fine aggregate was crushed stone dust from Kgale Quarries Pty (Ltd), Gaborone of maximum nominal size of 4.75 mm. The properties of fine and coarse aggregates are presented in Table 1. The particle size distribution curves of the aggregates are plotted in Fig. 2. It is obvious that the fine and coarse aggregates employed as constituents of the concrete in the study are well-graded. Potable water of pH of 7.1 which conformed to the requirements of BS 3148 [16] was used in mixing the aggregates and cement. The aggregates were free from deleterious materials and the physical properties were carried out in accordance with BS 812 [17]. The properties of cement such as consistency, setting times, soundness and compressive strength are summarized in Table 2. The particle size distribution curve and other parameters of the cement (OPC) are shown in Fig. 3 and Table 3.

(a) Dry firewood for fuel

(b) Residue of firewood after combustion

Fig. 1: Dry firewood before and after combustion

Table 1: Properties of aggregates

	Quarry dust	Crushed granite
Specific Gravity	2.64	2.70
Bulk Density (kg/m^3)	1240	1464
Moisture content	4.09	0.6
Fineness modulus	3.00	6.15
Aggregate Crushing Value (%)		12.9
Impact Value (%)		7.13

Crushed stone dust (sand) as fine aggregate

Crushed granite as coarse aggregate

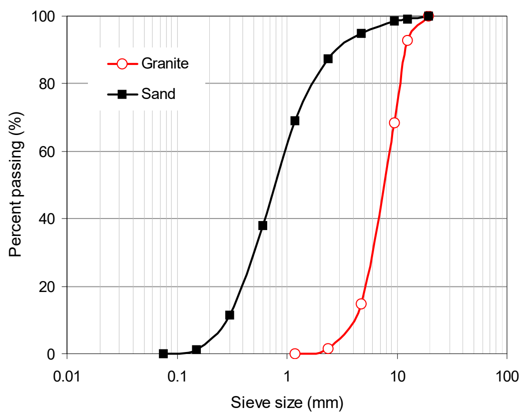

Fig. 2: Samples of particle size distribution of fine and coarse aggregates

Table 2: Physical properties of cement

Standard Consistency (%)	30
Specific gravity	3.13
Initial setting time (min) - minutes	120
Final setting time (max) - minutes	422
Soundness (mm)	1.0
Compressive strength (N/mm^2)	
3 days	27
7 days	53

B. Preparation and physical properties of firewood ash

The firewood residues were sourced from Tlokweng (South-east district), Molepolole (Kweneng district) and Kang (Kgalagadi district) and designated as samples S1, S2 and S3. The residues from regular combustion of firewood after cooking were subject to controlled combustion in an industrial oven at a temperature of 1000°C for 2 hours. The specific surface area and pore size distribution of FWA was determined by a single port Gas Sorption Analyzer Coulter Omnisorp 100 using the Brunauer–Emmett–Teller (BET) test method. The pH was determined by preparing a 20% FWA to liquid ratio suspension using deionized water. The mixture was shaken for 5 minutes and left for 3 hours to equilibrate before measuring the pH in accordance with BS 7755 [18].

C. Samples preparation for chemical analysis of firewood ash

The chemical composition of samples of FWA was determined by X-ray fluorescence (XRF) using dispersive energy spectrophotometer. The elemental oxide contents in the FWA especially the silicon oxide (SiO_2) or silica present was a principal criterion for a good pozzolan. Loss on ignition (LOI), which is a measure of percentage of organic content (carbon) in the material, was determined by oven drying 2–3 g of material at 105°C to constant mass before calcining at 1000°C for 2 hours, cooling and re-weighing. The loss in weight is expressed as a percentage of the original sample. The chemical constituents of the FWA sourced from three different districts of Botswana namely Tlokweng, Molepolole and Kang and subjected to controlled combustion in an industrial oven to a temperature of 1000°C for 2 hours as analyzed by x-ray fluorescence (XRF).

D. Mix proportioning and casting of concrete specimens

Four different concrete mix proportions designated C_0, C_1, C_2 and C_3 with a fixed water-cement ratio of 0.49 were considered for the study. Concrete mixture C_0 was the control mix without any FWA, while C_1, C_2 and C_3 are mixes with 10%, 20% and 30% FWA contents, respectively. The total cementitious materials (TCM), fine and coarse aggregates were kept constant at 437 kg/m^3, 814 kg/m^3 and 984 kg/m^3 respectively representing a concrete mix ratio of 1:1.86:2.25 in proportion of cement, fine and coarse aggregates. The only difference in the concrete mix proportions C_0, C_1, C_2 and C_3 is the percentage FWA content corresponding to 0, 10, 20 and 30% of the total cementitious materials (TCM). Each concrete mix proportion was prepared in a rotating drum mixer. The aggregates and cement were placed in the drum and mixed in parts with water to ensure a better bond between the cement paste and the aggregates. All mixing and sampling of concrete were carried out in accordance with the procedures given in BS 1881. The mix proportioning computed using arbitrary volume method is presented in Table 3.

Table 3: Concrete mix proportion

Mix proportions	C_0	C_1	C_2	C_3
Cement (kg/m^3)	437	393	350	306
FWA (kg/m^3)	0	44	87	131
FWA/TCM ratio (%)	0	10	20	30
Water (kg/m^3)	214	214	214	214
Water/cement ratio	0.49	0.49	0.49	0.49
Fine aggregate (kg/m^3)	814	814	814	814
Coarse aggregate (kg/m^3)	984	984	984	984
All constituents (kg/m^3)	2460	2460	2460	2460
Average Slump (mm)	65	42	39	22

Three concrete cylinders of 150 mm diameter × 300 mm length each of 0, 10, 20 and 30% FWA contents were cast, cured and tested for split tensile strength at 28 days. Also, a total of thirty-six (36) concrete cube specimens of size 150 mm (representing 12 cubes for 0, 10, 20 and 30% FWA contents) were cast, cured and tested for compressive strength according to BS 1881. The compressive strengths of the specimens were determined from average crushing load of 150 mm cubes at 7, 14 and 28 days. Concrete specimens were cast and then covered with thin polythene membrane to minimize moisture loss. The concretes were stored and tested in the laboratory under mean air temperature of 26 ± 1˚C. The specimens were demoulded after 24 ± ½ hours and then transferred into a water-curing tank for the test periods.

IV. Results and Discussion

A. Physical properties of firewood ash

The particle size distribution analyzed by laser diffraction showed that FWA particles are distributed over the range 0.25–100 μm using Beckman Coulter LS-100. The specific gravity of FWA was determined by pycnometer. The loose bulk density of FWA was 810 kg/m^3. The pH of the ash was 10.3, the specific gravity was 2.25 and the BET surface area was 10.7 m^2/g. The results agreed with the findings of relevant literature in recent years. It is obvious from the particle size distribution of the FWA and ordinary Portland cement (OPC) shown in Fig. 3 and Table 4 that that over 60% of the material was finer than 50 μm.

The texture of as collected and oven-dried FWA was smooth. The effective size of OPC and FWA were 2.20 μm and 3.93 μm, respectively. The particle size of OPC corresponding to 30% and 60% cumulative passing were 7.08 μm and 15.09 μm, while the corresponding size for FWA were 11.59 μm and 36.97 μm, respectively. The coefficients of uniformity and curvature for the OPC were 6.88 and 1.52, while the corresponding values for FWA were 9.42 and

0.93. Although OPC is relatively denser than FWA, the physical properties showed that the particle size of the FWA was relatively larger and coarser than OPC as summarized in Table 4. FWA consisted of a heterogeneous mixture of variable particle sizes which are generally angular in shape.

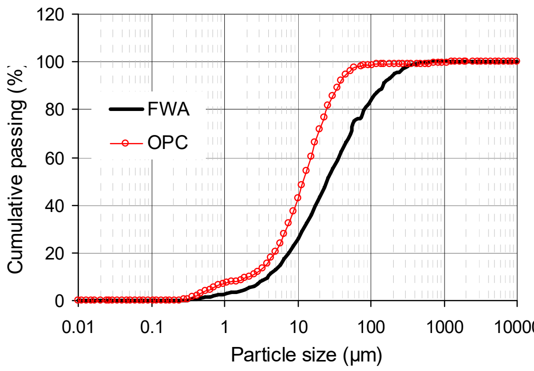

Fig. 3: Cumulative particle size distribution of FWA and OPC

Table 4: Properties of FWA and OPC

SCM	Particle size distribution parameters					
	Specific gravity	D_{10} (μm)	D_{30} (μm)	D_{60} (μm)	C_u	C_c
OPC	3.13	2.20	7.08	15.09	6.88	1.52
FWA	2.25	3.93	11.59	36.97	9.42	0.93

B. *Chemical composition of firewood ash*

It can be observed from the XRF analysis shown in Table 5 that combined silica, alumina and hematite (<10%) contents accounted for an average of 62.45%, which could be categorized as Class C fly ash. Likewise, silica and alumina contents accounted for 57.28% of the FWA constituents. The sum of SiO_2, Al_2O_3 and Fe_2O_3 was 62.45%. Also, the Fe_2O_3 content, which is a reactive oxides, is relatively low (5.16% > 10%) compared to as the silica and alumina. Even though the FWA could not be regarded as a pozzolan (SiO_2 + Al_2O_3 + Fe_2O_3 = 62.45% < 70%), it still qualified as an active mineral addition (Class C fly ash) in partial replacement of cement in concretes and mortars. These results, however, are at variance with the findings of Naik et al. [4], Udoeyo et al. [9], and Abdullahi [15].

With the CaO content (> 10%), the ash is expected to behave as an inert mineral residue. The low phosphorus content of 1.44% indicated by P_2O_5, explained why FWA is not environmentally friendly for agricultural purposes or ultimate disposal in landfill. The low value of LOI (< 10%) shows that organic content in the FWA is relatively low, thereby enhancing the binding properties of the ash when mixed with cement.

Table 5: Chemical composition of FWA

Constituents	Chemical composition by weight of FWA			
	S1	S2	S3	Average
SiO_2	44.46	48.37	50.7	47.84
Al_2O_3	8.62	11.5	8.2	9.44
Fe_2O_3	7.71	5.68	2.1	5.16
CaO	15.88	10.61	19.6	15.36
MgO	1	2.78	6.5	3.43
K_2O	8.62	4.41	2.8	5.28
Na_2O	0.45	4.07	2.1	2.21
MnO	0	0	0	0.00
TiO_2	0.09	0.52	1.2	0.60
P_2O_5	1.63	1.25	0	1.44
SO_3	2.36	1.81	0.1	1.42
LOI	9.18	9	6.7	8.29
Total	100	100	100	100

C. *Setting times of cementitious materials*

The binding quality of Portland cement paste is due to the chemical reaction between the cement and water, called hydration. Portland cement is not a simple chemical compound, it is a mixture of many compounds. Four of these make up 90% or more of the weight of portland cement: tricalcium silicate, dicalcium silicate, tricalcium aluminate, and tetracalcium aluminoferrite. The purpose of the setting time test is to determine the time that elapses from the moment water is added until the paste ceases to be fluid and plastic (called initial set) and the time required for the paste to acquire a certain degree of hardness (called final set). The initial and final sets of the FWA-blended cement showed linear trends for both the initial and final sets as shown in Fig. 4. In line with standard requirements, the initial and final setting times for the four mixes were neither less than 30 minutes nor greater than 600 minutes.

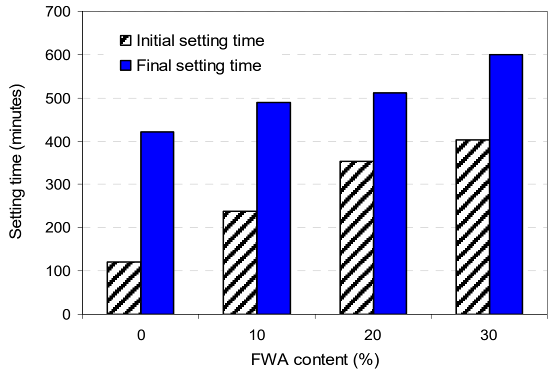

Fig. 4: Initial and final setting times for FWA-blended cement.

The margin the initial and final set times narrowed down as the FWA increased from 0% to 30%. In addition, the setting times increased linearly as the FWA content increased with the final setting times increasing at about 58% of the rate of increase in the initial setting times.

D. *Properties of fresh FWA-blended cement concrete*

Concrete must always be made with a workability, consistency, and plasticity suitable for job conditions. Workability is a measure of how easy or difficult it is to place, consolidate, and finish concrete. This study assessed the workability of the mix proportions using slump and compaction factor tests. Fig. 5 shows the test results of workability of the four concrete mixtures. The slump of the concrete mixes decreased linearly with increase in FSA content. The control specimen C_0 had the highest slump of 65 mm, while C_3 had the lowest slump value of 22 mm. It is evident from the test results that slump except for mix C_3 fell within the recommended range for plain and reinforced concrete (i.e 25 mm < slump < 75 mm). The relationship between slump and FWA content is almost perfectly linear in the form of relation $s = -13.2c + 75$ (R^2 = 0.93), where s and c are the slump and FWA content respectively.

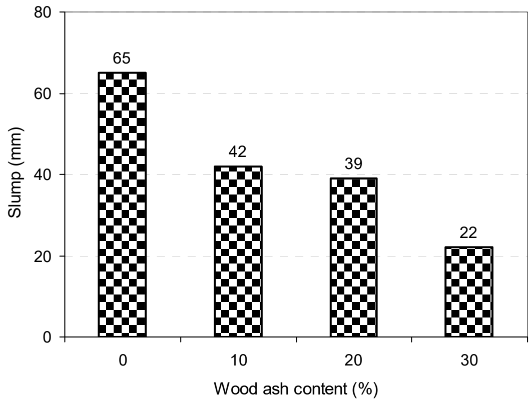

Fig. 5: Workability of FWA-blended cement concrete

The percentage difference in the slump of C_1, C_2 and C_3 with respect to the control mix was 35%, 40% and 66%, respectively. This shows that there is a very steep loss of workability as the FWA content in the mix increased from 20% to 30%. It is therefore evident that mix C_3 would require super-plasticizer to enhance the workability of the concrete mixture to be suitable for practical concrete construction.

E. *Compressive strength of FWA-blended cement concrete*

Compressive strength is the measured maximum resistance of a concrete specimen to axial loading. The 7th day strengths of concrete are often estimated to be about 75% of the 28th day strength [19-20]. As shown in Fig. 6, the 7th day strengths of C_0, C_1, C_2 and C_3 were 50.9%, 55.2%, 51.3% and 53.6% of the 28th strength which fell below the findings. The compressive strength of concrete specimens with respect to the FWA-blended cement concrete is parabolic. The loss of compressive strength due to different levels of FWA contents in the mix at 7 days, 14 days and 28 days curing ages is presented in Fig. 7.

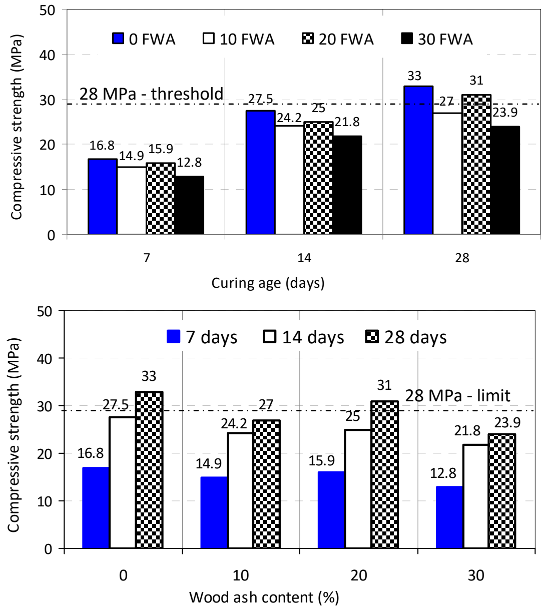

Fig. 6: Compressive strength of FWA-blended cement concrete

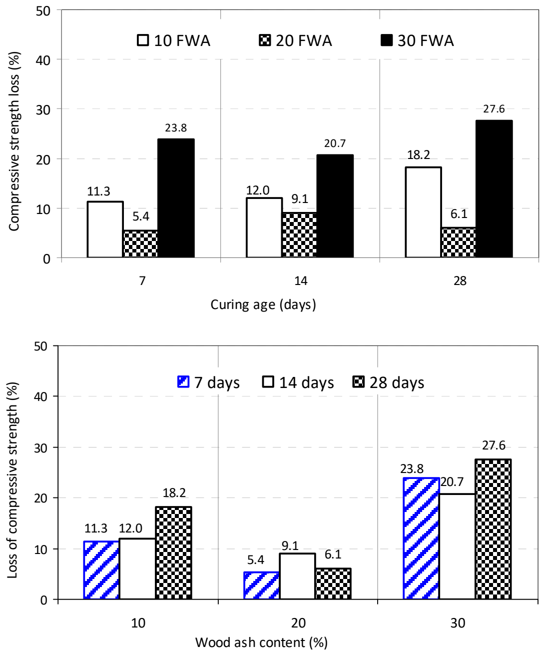

Fig. 7: Loss of compressive strength of FWA-blended cement concrete

As shown in Fig. 6, the optimal FWA content for maximum compressive strength was 20%. For all the four mixtures at the 7 days, 14 days and 28 days curing ages, it was found that the control mix had the highest compressive strength. The 28^{th} day compressive strengths of concrete mixtures C_1, C_2 and C_3 were 82%, 94% and 72% of the compressive strength of the control mix C_0. For a target strength of 28 MPa considered in the study, it is evident that the control and C_2 (with 20% FWA content) mixtures produced compressive strengths higher than the threshold value. The compressive strength-FWA content relations for all the curing days are perfectly of cubic polynomials and less of quadratic ($0.55<R^2< 0.80$) and linear ($0.54<R^2< 0.80$) relations.

In addition, it is evident from Fig. 7 that 20% FWA content as cementitious addition in the concrete mixture gave the least loss of compressive strength of 5.4%, 9.1% and 6.1% at 7 days, 14 days and 28 days curing ages respectively. These were within the acceptable limits with respect to the target strength of 28 MPa. On the other hands, 10% FWA as partial replacement for cement produced 11.3%, 12% and 18.2% loss of compressive strength at 7 days, 14 days and 28 days curing ages respectively. Worst of all, 30% FWA cementitious content gave 23.8%, 20.7% and 27.6% loss of compressive strength at 7 days, 14 days and 28 days curing ages respectively, which were the highest level of compressive strength loss in concrete.

F. *Split tensile strength of SSA-blended cement concrete*

The tensile strength of concrete is about a tenth of the compressive strength. It is determined by loading a concrete cylinder across a diameter in accordance with BS EN 12390 [21]. The relationship between the split tensile strength of the concrete mixes and the SSA content was simply quadratic or more perfectly cubic as shown in Fig. 8.

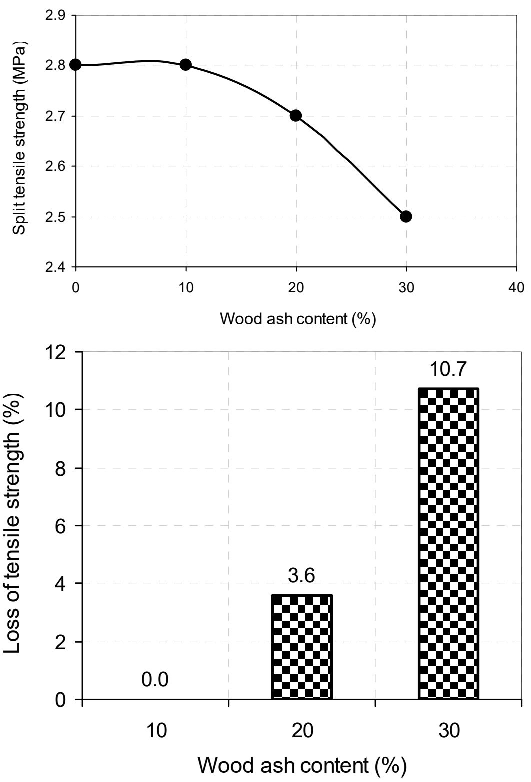

Fig. 8: Split tensile strength and loss of tensile strength for FWA-blended cement concrete

The split tensile strength for the four mixtures was in the range 2.5–2.8 MPa. The 28th day tensile strength of concrete is constant for the control C_0 and mix C_1 (having 10% FWA content). These results were in agreement with the findings of Naik et al. [4] and Udoeyo et al. [9]. The tensile strength dropped at an increasing rate from 20% to 30%. The tensile strength as the percentage of the compressive strength showed that C_0, C_1, C_2 and C_3 were 8.5%, 10.4%, 8.7% and 10.5%. All the concrete mixtures met the standard requirements where the direct tensile strength of normal concrete should fall within the range 8 - 12% of the compressive strength and is often estimated as 0.4 to 0.7 times the square root of the compressive strength (in MPa) [19]. The findings revealed that the 3.6% split tensile strength loss corresponding to 20% FWA content is still within the permissible range.

G. *Water absorption*

Concrete specimens absorbed more water as the ash content increased. The absorption of fly-ash concrete is about the same as concrete without ash, although some ashes can reduce absorption by 20% or more [20]. Water absorption for 28 days curing age was perfectly linear with respect to the FWA content in the mixes as shown in Fig. 9.

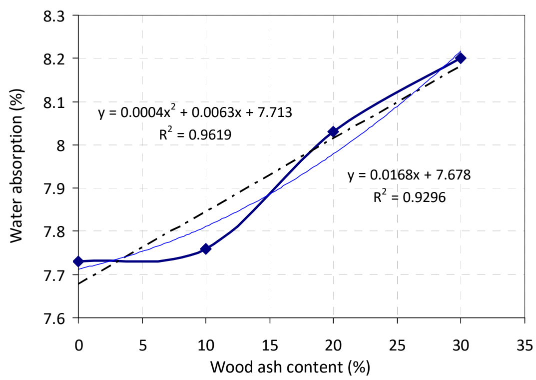

Fig. 9: Water absorption of FWA-blended cement concrete

However, the rate of increase in water absorption decreases with the age of concrete. It is evident from the study that FWA increased the water absorption of the concrete specimens of mixes C_0, C_1, C_2 and C_3 both linearly (R^2 = 0.93) and quadratically (R^2 = 0.96). The water absorption of the hardened concrete of the four mixes were between 7.7% and 8.2%. This is very close to 10%, which is the percentage water absorption value accepted for most construction materials.

V. CONCLUSION

This work has confirmed the potentials of FWA from dead firewood sourced Tlokweng, Molepolole and Kang from different districts of Botswana as supplementary cementitious material in partial replacement of cement in concrete production. Different FWA content between 0 and 30% at equal interval of 10% was investigated to evaluate the factors that could enhance the performance concretes. The following conclusions were drawn from the experimental study conducted on the suitability of FWA as supplementary cementitious addition in concrete.

1. The firewood ash from three different sources in Botswana qualified as pozzolan (combined contents of SiO_2, Al_2O_3 and Fe_2O_3 was 62.45%, while CaO content was 15.4%.
2. The FWA could be regarded as Class C fly ash with slightly high calcium content and is suitable as supplementary cementitious material (SCM) for cement-based concretes and mortars.
3. The initial and final setting times for the hydration of cement at different levels of FWA contents were within the acceptable limits of 30 minutes (minimum) and 600 minutes (maximum).
4. The workability of concrete with FWA-blended from 0 to 20% was found to be within the specification plain and reinforced concrete. However, concrete mix with 30% FWA fell below the 25 mm minimum slump value and would require super-plasticizer for practical applications.
5. The water absorption of concrete at 28th day curing age was acceptable for all the concrete mixtures even though water absorption increased linearly with FWA contents.
6. The permissible FWA content for compressive and split tensile strength was 20%.

Acknowledgments

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