Application of Wood Waste Ash in Concrete Making: Revisited

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Abstract Portland cement production is a carbon dioxide trigger responsible for almost 5% of the worlds CO_2 emissions. Pozzolanic inclusions could contribute to sustainability particularly if they are derived from waste. Managing solid waste is increasingly becoming a global challenge as a result of increasing volume of accumulated waste from industrial and agricultural by-products. Environmental concerns as well as economic implications related with disposal of these wastes have prompted many researches in order to provide viable solutions. Recycling of these waste materials into the construction industry seems to be a more promising and viable alternative most especially in the manufacturing of greener and sustainable concrete material. Wood ash (WA) is a by-product derived from incineration of wood as well as its products such as sawdust, wood bark and chips. This paper presents an overview on investigations performed on the applicability of this material in mortar and concrete making. Specifics on physical, chemical,

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mineralogical and elemental characteristics of the waste material are discussed. It highpoints the impact of wood ash on workability, compressive and flexure strengths, water absorption, drying shrinkage, carbonation, alkali–silica reaction (ASR) and chloride permeability of concrete.

Keywords Concrete · Recycling · Wood ash · Mechanical properties
Durability · Supplementary cementitious material

1 Introduction

Annually, more than 1 m^3 of concrete is estimated to be produced globally per person [1] making it the most widely used construction material. Portland cement which is the main ingredient in concrete is mostly criticized due to its environmental influence arising from the clinker production [2, 3]. Currently, about 3 billion tonnes of cement is consumed world over [4]. In fact, up to 1.5 billion tonnes of CO_2 is released into the atmosphere yearly by cement production plants arising from the manufacture of portland cement amounting to almost 5% of CO_2 emissions worldwide and if this unwanted trend lingers, the result will likely increase to 6% by the year 2015 [5, 6]; hence, all efforts to fight this ugly scenario become imperative.

More so, the tremendous increase in demand for energy especially in developing countries has led to search for renewable energy source as alternatives to fossil fuels due to outcry by environmentalist in order to compensate for the available ones.

A recent survey by [7] has projected an increase in world energy consumption of 47% from 2007 to 2035. In Malaysia, total electricity generated using renewable energy sources in 2009 amounts to only 5.5% while 94.5% was generated through fossil fuels like coal, oil and natural gas. The Malaysian timber processing sector stands to be a prospective candidate as a source of renewable energy in order to compliment the electricity demand as it is regarded to be among the largest unexploited biomass resource in Malaysia [8]. Biomass from wood, namely, wood chips, sawdust and cut-offs represents the main waste material resulting from timber manufacturing industries [9]. Wood wastes remain the most preferred fuel for biomass kilns than herbaceous and agricultural waste because the combustion of wood wastes produces quite lesser residual and fly ash [10]. While the above said practices offers a practical solution to managing of the solid waste produced from the wood residues, a major problem associated with their prevalent usage as a fuel is the residual ash generated in substantial quantities of which the industry is yet to find widespread empirical applications regarding the recycling of this ash material [11].

In this light, several investigations have established the success of wood ash as material replacing cement to fabricate structural concrete possessing adequate mechanical as well as durability characteristics [11–14]. These research findings could provide twofold answers regarding the solid waste management issue and enhancing the sustainability of the construction industry.

2 Properties of Wood Ash

The beneficial use of wood waste ash is strongly governed by their chemical and physical characteristics which vary considerably depending on several factors [13]. These characteristics are mostly influenced by the tree species, conditions and areas where the trees are grown, temperature and means of incineration as well as the method employed during the collection of ash [15, 16]. Thus, this necessitates the appropriate characterisation of the ash before its utilization as a constituent material in blended cement and concrete.

The chemical composition as well as the quantity of wood ash produced is strongly governed by the temperature of combustion in the furnace. Incinerating at higher temperatures above 1000 °C results in a lower yield of wood ash generated while at same time results to a significant reduction in the amount of carbonate mainly arising from the chemical disintegration of the above-mentioned chemical compound. The physical properties of the resulting ash after incineration are influenced significantly by the various types of combustion technologies adopted. Generally, the resulting wood ash generated in fluidized furnaces is largely fine fly ash while those generated in the grate-fired incinerators are coarser in nature which tends to reside in the combustion unit as bottom ash. The chemical properties of the resulting wood ash after incineration of wood waste is reliant on the tree species from which it was obtained. The chemical composition of SiO_2, Al_2O_3, Fe_2O_3 and CaO, which determines the acceptability of wood ash as pozzolana, differs greatly from one tree species to another [11]. Differences in the chemical characteristics of wood ash generated from various tree species are shown in Table 1.

2.1 *Physical Properties*

The pozzolanic as well as hydraulic reactivity of wood waste ash is significantly affected by physical properties of the ash; hence, variations in these properties demand proper characterization of the wood ash obtained from various sources before use as cement replacing material for concrete production.

Cheah and Ramli [12] assessed the physical properties of high calcium wood ash (HCWA) used as partially replacing cement. The specific gravity, surface area and median size d_{50} were found to be 2.52, 1087.1 m^2/kg and 5.16 μm, respectively. In a different research to study the transport properties of (HCWA)—densified silica fume (DSF) hybrid mortar, Cheah and Ramli [24] reported that the wood ash had a surface area and median size d_{50} of 8.39 μm and 611 m^2/kg. The fine grading of the wood ash is attributed to an efficient grinding action.

Table 1 Summary of differences in chemical composition of wood ash

Author/compound	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	TiO_2	K_2O	Na_2O	SO_3	C	P_2O_5	LOI (%)
Elinwa and Mahmood [17]	67.2	4.09	2.26	9.98	5.8	–	–	0.08	0.45	–	0.48	4.67
Udeoyo and Dashibil [18]	78.92	0.89	0.85	0.58	0.96	–	–	0.43	–	17.93	–	8.4
Elinwa and Ejeh [19]	67.2	4.09	2.26	9.98	5.8	–	–	0.08	0.45	–	0.48	4.67
Naik et al. [20]	32.4	17.1	9.8	3.5	0.7	0.7	1.1	0.9	2.2	–	–	31.6
	13	7.8	2.6	13.7	2.6	0.5	0.4	0.6	0.9	–	–	58.1
	50.7	8.2	2.1	19.6	6.5	1.2	2.8	2.1	0.1	–	–	6.7
	30	12.3	14.2	2.2	0.7	0.9	0.5	0.5	2.1	–	–	35.3
	8.1	7.5	3	25.3	4.5	0.3	3.3	3.3	12.5	–	–	32.8
Abdullahi [21]	31.8	28	2.34	10.53	9.32	–	10.38	6.5	–	–	–	27
Rajamma et al. [22]	41	9.3	2.6	11.4	2.3	0.4	3.9	0.9	–	–	0.9	–
	28	6.2	2.2	25.4	5	0.3	3.2	3.3	–	–	0.9	–
Cheah and Ramli [12]	28	4.1	2.5	39	10	0.13	7.4	1	1	2	3.9	7.22
Esteves et al. [23]	52.1	13.3	5.3	15.9	3.31	–	4.14	–	0.45	–	–	10.4
	25.1	11.3	5.18	40.1	6.63	–	2.07	–	1.12	–	–	3.5
Ramos et al. [14]	73.01	11.93	3.38	2.64	1.03	0.48	4.14	3.81	<0.05	–	0.59	1.47
Cheah and Ramli [24]	2.7	1.3	1.3	61	8.7	0.11	12	–	2.8	6.7	2.7	18
Berra et al. [25]	20.03	5.04	2.44	63.03	1.35	0.22	1.12	1.04	3.36	–	0.13	2.4

Esteves et al. [23] determined the particle size and specific surface (BET) of two wood ashes, namely, BFA1 and BFA2 in his study to assess the influence of the wood ashes in mitigating the effect of ASR. The reported values of particle size and surface areas for BFA1 are 17 µm and 28.52 m^2/g while for BFA2 are 21 µm and 1.74 m^2/g, respectively. Although both samples have similar size distributions but the surface areas was completely different. The greater value for BFA1 could be explicated by the higher quantity of unburnt carbon and the irregularity pattern in the shape of the particle.

Berra et al. [25] reported the average particle sizes and densities of three wood ashes WBFA1, WBFA2 and WBFA3 for use as cement-based material as 135, 86 and 179 µm while the densities of the wood ashes ranged between 2.35 and 2.76 g/cm^3, respectively. The densities of the wood ashes were similar to that achieved by coal fly ash and considerably lesser than those of standard cement. Hence, by partially replacing cement with wood ash, the weight of the blended material could be considerably reduced.

2.2 Chemical Properties

The chemical composition of biomass fly ash is an essential parameter which governs its suitability to be adopted as pozzolan in blended cement mixtures; hence, adequate characterisation is required. X-ray fluorescence (XRF) tests conducted in numerous researches had established substantial amounts of calcium and silica in samples of the ash investigated (Table 1). In some of these studies, the wood ash could be classified as possessing pozzolanic reactivity while in others they might be regarded as possessing hydraulic reactivity.

Cheah and Ramli [12] analysed the chemical composition of HCWA to be used as cement replacing material. Results obtained by X-ray diffraction (XRD) analysis revealed the main chemical phase to be Monticellite ($CaMgSiO_4$), Arkemanite ($CaMgSiO_2$) and Pectolite ($HNaCaSi_3O_9$). The presence of these compounds is in accordance with the results obtained from the XRF examinations (Table 1) which showed the presence of considerable amounts of CaO, MgO and SiO_2 in the ash. The XRD pattern which shows a diffuse broadband between 24° and 37° on the 2θ scale is indicative of the glassy nature of the silicate minerals.

Esteves et al. [23] reported the principal crystalline phases on BFA2 are quartz, periclase and calcite while those present in BFA1 are quartz, microcline and calcite. Variations are due to the differences in the chemical characteristics as shown in Table 1. The ashes can both be classified as type C in relation to those of coal incineration as they both contain more than 10% CaO as well as react both hydraulically and pozzolanically. XRD analysis performed by [25] revealed the existence of large quantity of amorphous phase of lime, calcite and quartz as the main crystalline phases.

3 Properties of Mortar and Concrete Incorporating Wood Ash

3.1 Standard Consistency

Cheah and Ramli [9] detected that the incorporation of HCWA at increasing percentages of cement replacement achieved a negligible rise in water demand of blended mixtures. This scenario could be mainly ascribed to similarity in the particle grading of the HCWA and OPC.

Cheah et al. [26] observed that as HCWA is gradually added into the blended system of HCWA-PFA geopolymer there is a corresponding rise in the water demand so as to attain standard consistency for the blended HCWA-PFA geopolymer paste This may be explained based on the porous nature and angular shape of the HCWA particles in comparison to PFA particles which normally exhibits a smooth and spherical nature.

3.2 Setting Time (Initial and Final)

According to [12], the addition of HCWA at levels of cement replacement up to 20% extends the initial and final setting times of the DSF cement paste. This situation could be advantageous as it gives more time for activities of transporting, placing and consolidation of the mortar or concrete. Cheah et al. [26] studied the synergistic effect of HCWA and PFA blended geopolymer binders with different arrangement ratios of between 0 to 100 and 100 to 0, respectively at 10% step increase for the purpose of fabricating building block. They concluded that increasing the mass proportion of HCWA leads to a significant increase in water demand of the blended paste. Also, paste having equal quantity of wood ash and fly ash exhibited a greater degree of both final and initial setting characteristics relative to blended paste containing either fly ash or wood ash only. This phenomenon is as a result of superior rate of reactivity in the former paste resulting in a quicker development of geopolymeric products that resulted in the subsequent stiffening of the paste.

3.3 Slump

Abdullahi [21] investigated the effect of wood ash on concrete slump by replacing cement with wood ash at varying proportions (0, 10, 20, 30 and 40%) with a mix design of 1:2:4. The result is presented in Table 2. Result depicts that mixes with higher contents of wood ash require a higher amount of water to attain satisfactory workability.

Table 2 Wood ash concrete slump test result [21]

HCWA content (%)	0	10		20	30	40
Water/binder actual ratio	0.6	0.66		0.67	0.68	0.69
Slump (mm)	30	35		40	40	35

Table 3 Slump of mortar with HCWA as cement replacement [9]

HCWA content (%)	0	5	10	15	20	25
Superplasticizer dosage (%)	1.85	1.85	1.85	1.98	1.98	1.98
Slump (mm)	90	70	50	50	50	50

Cheah and Ramli [9] reported the results of slump test of mortar samples incorporating different percentages of HCWA (0, 5, 10, 15, 20 and 25%) by weight of cement. The results are shown in Table 3.

From the results, it is clear that as cement replacement levels increases, there is a reduction in the slump of the mixes. As increment in the amount of HCWA continued, a higher dosage of superplasticizer was needed to retain the slump according to the desired range. Mixes with 15, 20 and 30% levels of HCWA addition achieved the same slump values at a constant dose of superplasticizer of 1.98%. These outcomes could be clarified due to the marginal higher surface area of HCWA compared to OPC.

3.4 Compressive Strength

Cheah and Ramli [12] studied the strength in compression of mortar mixes incorporating HCWA up to 90 days with HCWA content of 5, 10, 15, 20 and 25%. They concluded that the targeted strength of 40 MPa was attained for mortar mixtures having contents of HCWA up to 20%. Also, mortar mix incorporating 15% of HCWA achieved higher strength in compression than the control after extended curing regime of 90 days. Mortar having up to 25% HCWA exhibited compressive strength beyond 90% of control mix. Also, Cheah and Ramli [9] investigated the compression strength of HCWA-DSF hybrid mortar containing a constant amount of DSF (7.5% of cement weight) and varying proportions of HCWA ranging from 2 to 20% at step increment of 2%. They concluded that the strength in compression of mortar having HCWA contents of 2 and 4% was improved considerably at early and later curing periods. Mortar mix containing HCWA amount up to 14% in blend with 7.5% DSF by binder weight achieved comparable strength as the control mixture at 364 days.

3.5 Flexural Strength

The strength in flexure of mortar mixes incorporating HCWA up to 90 days with HCWA content of 5, 10, 15, 20 and 25% was investigated by [12]. They established that an increase in flexural strength is achieved at 5% HCWA content at all ages relative to the control mix. Cheah and Ramli [9] studied the flexural strength of HCWA-DSF hybrid mortar containing a constant amount of DSF (7.5% of cement weight) and varying proportions of HCWA ranging from 2 to 20% at step increment of 2%. They established that mortar mix having up to 8% HCWA in parallel with 7.5% DSF achieved higher flexural strength in comparison with the control mix. Also, up to 20%, HCWA could be utilized together with 7.5% DSF to obtain comparable flexure strength relative to control mortar.

3.6 Drying Shrinkage

Cheah and Ramli [12] examined the drying shrinkage of mortar mixes fabricated by replacing cement with HCWA at varying percentages (5, 10, 15, 20 and 25%) of the total weight of binder. They reported that the utilization of HCWA at 10% as supplementary cementing material lead to the decline in overall drying shrinkage of mortar on exposure to air curing.

3.7 Carbonation

Cheah and Ramli [12] examined the effect of HCWA on the resistance to carbonation of mortar mixes fabricated by replacing cement with HCWA at varying percentages (5, 10, 15, 20 and 25%) of the total weight of binder. The result indicated that the resistance to carbonation of mortar mix having 5% HCWA was enhanced upon comparison with the control, and that the inclusions of above 5% HCWA could result to a lesser degree of carbonation. In another study [24], examined the resistance to carbonation of mortar mixtures produced by replacing cement with HCWA at varying percentages (2, 4, 6, 8, 10, 12, 14, 16, 18 and 20%) in combination with 7.5% DSF of total weight of binder weight. They reported that an optimum level HCWA replacement to achieve enhanced carbonation resistance is 10%. This enhancement could be attributed to the refinement in pore structure of the mortar mix with HCWA compared to the control mortar.

Ramos et al. [14] conducted research on the carbonation resistance of mortar produced with 0, 10 and 20% WWA obtained from a power plant as replacement for cement. They, however, concluded that the depth of carbonation for the blended mixtures was higher than the control and that depth of carbonation increases with an increase in WWA levels. They attributed this trend to possible reduction in portlandite resulting in a decrease in pH.

3.8 Alkali–Silica Reaction

Ramos et al. [14] conducted research on the influence of WWA on resistance of alkali–silica reaction of mortar produced with 0, 10 and 20% WWA obtained from a power plant as replacement for cement. From the obtained results, it is evident that the control set had exhibited possible detrimental expansion in accordance with ASTM 1567 (greater than 0.1% beyond 14 days in sodium hydroxide) for the related type of cement and sand used. They concluded that WWA was successful in inhibiting the expansion due to ASR and that higher content of WWA could lead to lesser expansion.

4 Conclusions

- Wood ash quality and quantity are depended mainly on the temperature as well as the technology of combustion and the tree species the wood biomass is derived. Thus, appropriate characterisation of wood ash becomes imperative before its implementation in cement-based materials.
- Incorporating wood ash as a cement replacing material negatively affects workability of concrete.
- Presently, code of practice regarding the usage of wood ash is non-existent. However, characteristics of wood ash demonstrate that ASTM C 618 'Standard specification for coal fly ash and raw or calcined natural pozzolan for use as mineral admixture' can be adopted for wood ash.
- Generally, the inclusion of wood ash in cement-based mixtures decreases the mechanical strength of the mixtures.
- Improved durability performance could contribute to sustainability in construction.

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