

## A Potential Environmental Sustainability of Wood Ash in Normal and Geopolymer Concrete – A Review

Muhammad Nura Isa<sup>1,2</sup>, Hanizam Awang<sup>1\*</sup>, Khairunisa Muthusamy<sup>3</sup>

<sup>1</sup> School of Housing, Building and Planning, Universiti Sains, Malaysia, E49, 11800 Gelugor, Penang, Malaysia

<sup>2</sup> Faculty of Environmental Technology, Abubakar Tafawa Balewa University, Bauchi, Nigeria

<sup>3</sup> Faculty of Civil Engineering Technology, Universiti Malaysia Pahang, 11800 Gelugor, Penang, Malaysia

\* Corresponding author's e-mail: hanizam@usm.my

### ABSTRACT

The production of cement for concrete has led to the emission of carbon dioxide (CO<sub>2</sub>) into the atmosphere, which has contributed to global warming. Moreover, the excessive amount of industrial waste from biomass energy production landfilled in our environments is continuously causing sustainability challenges. However, several studies were carried out to ascertain the possibilities of using these waste materials in concrete production to address the cement and waste disposal sustainable issues simultaneously. The present study reviewed multiple studies carried out on wood ash (WA) application in both normal and geopolymer concrete with an emphasis on fresh, hardened, and durability properties. WA can be used to replace cement in conventional mortar/concrete at up to 20% replacement level, similarly, it was revealed that WA can be effectively utilized to replace ground granulated blast furnace slag (GGBS) or pulverized fly ash (PFA) at up to 50% replacement level in geopolymer mortar/concrete production. The sustainability impacts of WA utilization in concrete production were presented and discussed. Results of these findings revealed its suitability as supplementary cementitious material, but still there exists a gap in its utilization in geopolymer concrete.

**Keywords:** waste management; sustainability; concrete; geopolymer; properties.

### INTRODUCTION

Recently the world has witnessed massive population growth which causes rapid urban, economic, and infrastructural development. The development of our cities and towns has resulted in a substantial demand for energy, buildings, and civil engineering structures. The demand for energy, which is largely derived from fossil fuels, has resulted in its widespread combustion, which releases hazardous gases into the atmosphere and contributes to global warming. Carbon dioxide (CO<sub>2</sub>), the significant contributor to global warming has been increasing over the last decade, the total CO<sub>2</sub> emissions from energy consumption was reported to be around 32,578.645 million tonnes in 2011 [1]. Moreover, it is reported that this gas is responsible for around 65% of global

warming [2]. Other forms of energy, such as biomass energy, are currently being considered as alternatives to fossil fuels. Although the use of biomass energy is a positive development but has resulted in the generation of other waste materials such as fly ashes, which are mostly dumped in landfills. With the excessive CO<sub>2</sub> generated from the cement manufacturing and aggregates excavation processes, the building industry has been identified as one of the primary drivers of global warming [2–4]. Concrete has been classified as the second most used material on earth [5, 6]. The global consumption of concrete demonstrates the enormous amount of cement required [7]. It has been reported that the production of ordinary Portland cement (OPC) emits an equivalent amount of CO<sub>2</sub> into the atmosphere for every ton of cement produced [8–10]. In 2015 alone, it was

estimated that cement produced was about 4.6 billion tonnes [9], signifying the amount of CO<sub>2</sub> emitted into the atmosphere which directly affects global sustainability.

The quest for global sustainability has resulted in the discovery of pozzolanic materials, that are locally available, renewable, and environmentally beneficial, and can be utilized in concrete production as cement replacement. These materials include rice husk ash (RHA), wood ash (WA), ground granulated blast slag (GGBS), fly ash (FA), palm oil fuel ash (POFA) etc. [11–13]. Pozzolans are usually agricultural or industrial wastes or even naturally occurring materials that contain reactive silica [15,16], mainly from the products of biomass energy generation such as POFA and WA. Channelling these wastes for development of building material product to cater the need of construction industry would decrease waste thrown to environment and saves the use of lands as waste dumping area. Thus, this study reviews the inclusion of WA in normal and geopolymer concrete.

## BIOMASS ENERGY AND GLOBAL SUSTAINABILITY

The global energy consumption is steadily rising due to urbanization and population increase. Fossil fuel is still the world's primary source of energy. Although, due to a global pandemic that resulted in a significant drop in transportation demand, the global fossil fuel production fell by around 5% in 2020 compared to 2019 [24]. Despite this decline in production, fossil fuel continues to be the most widely used energy source, accounting for more than 81% of total production in 2019 compared to previous years. However, this finite, exhaustible energy source will be unable to meet the world's expanding energy demand over the next 100 years [25] and also can cause serious environmental issues. The widespread usage of fossil fuels since the industrial revolution has increased CO<sub>2</sub> atmospheric concentrations by more than 30%, with an annual increase of 0.5% as predicted, posing a severe threat to world sustainability [18].

According to Petinrin & Shaaban [16], energy supply in Malaysia is expected to increase from 65.9% Mtoe in 2015 to 130.5% Mtoe in 2030 at a growing rate of 2.8% per annum, mainly from fossil fuel. To reduce the country's

over-dependency on fossil fuels, other energy sources are now considered a possible alternative [17]. After petroleum, gas, coal, and hydro, the Malaysian government has in recent decades embraced biomass as a fifth fuel resource [1]. In many European, Asian, and African countries, biomass has also been widely employed to generate energy [6, 18, 19]. Biomass derived from wood wastes is a carbon-neutral fuel, absorbing the same amount of CO<sub>2</sub> during growth as it releases after combustion, and it is preferred over other biomasses because of less residual formation [20, 21].

One of the major generators of waste on the planet is the timber industry. It was reported that from 1992 to 2010, about  $98.2 \times 10^7$  m<sup>3</sup> of WA waste were generated globally [22]. In Malaysia, it was reported that wood industries were among the fastest-growing manufacturing industries in the country and are considered generators of a vast number of wastes [23]. Part of ways of minimising the wood wastes is its utilisation as biomass energy in the generation of electricity for the consumption of the wood companies or other industries. Eshun et al. [24] reported that many wood industries use a tremendous amount of wood waste in steam boilers to dry wood products. Also, sawmills use thermal combustion process to minimise these wastes. This process produced more solid wastes as WA, which may cause environmental and health problems if not carefully handled. According to Cheah & Ramli [20], the delicate matter from the disposed of WA may result in respiratory health problems to many people residing near the sites of these wastes disposal. This problem will be more severe in recent years with the new respiratory-related diseases such as Covid-19. Today, the major wastes management practice of WA remains landfill disposal causing both environmental and health issues directly affecting the global sustainability.

Many studies have been conducted over the last two decades to investigate the addition of WA in mortar/concrete production as partial replacement of cement to provide means of managing the WA which could otherwise be landfilled. It was revealed that the substitution of cement with high calcium wood ash (HCWA) at 15% replacement level could produce a mortar with promising strength and better durability properties [25]. Similarly, some researchers investigated the usage of WA in geopolymer concrete to limit the

external alkaline activators utilization. The results showed that the WA alkalinity contributes to the dissolution rate of aluminosilicate compounds in the binder material, improving its mechanical properties [26]. WA is a highly potential but unfortunately abandoned resource, hence, more research needed to be carried out to absorb WA into the construction sector.

## ORIGIN, CHEMICAL AND PHYSICAL PROPERTIES OF WOOD ASH

Wood waste is primarily a byproduct of timber processing industries, which came in form of ash and clinkers [27]. WA is produced mainly through the combustion of wood products in power plants, paper mills, sawmills and other wood-consuming related sectors [22]. This process produced a significant amount of WA, which was estimated to be around 5% to 15% of the total amount of the processed biomass [28]. Although these wastes come from a wood source, several factors may affect their quality and chemical composition [29–31]. Some of these factors include the temperature used during the combustion process, the furnace's type, and hydrodynamics, as well as the wood's specie [20]. They further noted that the pozzolanic oxide compounds of WA vary from different species of trees. Also, with the classification of wood, it was noted that hardwood produces more ash than softwood [32]. The plain microscopic observation of WA shows the dominance of crystalline phase with similar optical characteristics corresponding to calcite as shown in Figure 1 [33, 34]. They also observed the existence of fine crystals with a 1–2  $\mu\text{m}$  dimension. The study further revealed the particle size of the WA as mostly nano-size due to their delicate dispersion nature. The x-ray diffraction analysis revealed that the primary crystal forms of the WA are calcium carbonate ( $\text{CaCO}_3$ ), silicon dioxide ( $\text{SiO}_2$ ) and fairchildite ( $\text{K}_2\text{Ca}(\text{CO}_3)$ ) and highest loss of ignition (LOI) value of 19.6% was determined, which revealed the high content of unburned carbon present in the ash.

Grau et al. [35] reported some physical properties of WA in their recent studies. The WA was reported to include about 25.4% fine particles of less than 75  $\mu\text{m}$ , specific surface area, specific gravity, and pH value of 12,025–14,025  $\text{m}^2/\text{kg}$ , 2.5 and 12.57 respectively. A significant degree of particle shape irregularity and surface porosity

resulted in a high specific surface area as opined by [20]. The WA's scanning electron microscopy (SEM) analysis revealed its shape as a sub-angular shape with particle size ranging from 10–200  $\mu\text{m}$  [35]. In similar research by Rollakanti et al. [36], an uncontrolled burnt WA was used, the WA was obtained by burning wood in an open place, collected, and sieved through a 75  $\mu\text{m}$  sieve. The fineness and specific gravity of the WA were 5.60% and 2.96, respectively.

Chowdhury et al. [37] reported the primary composition of WA in their research as  $\text{SiO}_2$  of 65.30%, 4.25% alumina, and 2.24 ferric, the total Silicon dioxide ( $\text{SiO}_2$ ), aluminium oxide ( $\text{Al}_2\text{O}_3$ ) and iron oxide ( $\text{Fe}_2\text{O}_3$ ) was 71.79% conforming with the minimum 70% of class F and N pozzolana as classified in ASTM C618 [38]. However, other researchers reported the primary composition of the wood ash as calcium oxide ( $\text{CaO}$ ) with a bit of composition of  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$  and  $\text{Fe}_2\text{O}_3$ ; according to their reports, the wood ash did not meet the minimum requirements of ASTM C618 [38] but was seen to possess a high percentage of calcium within the range of 44.81% to 61.0%, this classified it as HCWA as reported in Table 1. Other researchers reported the chemical composition of WA with the total  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$  and  $\text{Fe}_2\text{O}_3$  of 52.5%, 57.8% and 58.77%, respectively [39–41], thus classifying the WA as class C according to ASTM C618 [38]. It was also noted that WA contains a significant amount of potassium oxide ( $\text{K}_2\text{O}$ ) of about 12.0 to 14.5, this shows the high alkalinity of WA [20, 35, 42]. Table 1 presents the different compositions of the WA as reported in various literatures. Pozzolanic activity

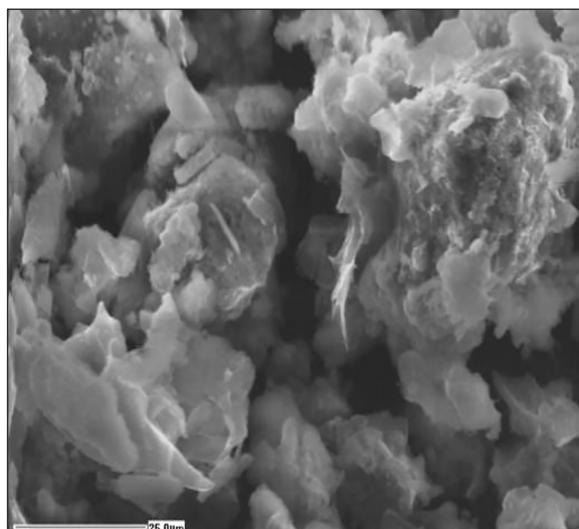


Fig. 1. Structure of wood ash [37]

**Table 1.** Chemical composition of WA in percentage (%) as reported in literature

Reference	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	CaO	MgO	TiO <sub>2</sub>	K <sub>2</sub> O	Na <sub>2</sub> O	SO <sub>3</sub>	P <sub>2</sub> O <sub>5</sub>	LOI
[43]	2.7	1.3	1.35	61.0	8.7	0.11	12.0	-	2.8	2.7	18.0
[44]	73.0	11.93	3.38	2.64	1.03	0.48	4.14	0.99	0.05	0.59	1.47
[37]	65.3	4.25	2.24	9.98	5.32	-	1.9	2.6	-	-	4.67
[40]	48.6	5.94	3.26	18.1	3.2	1.39	1.85	0.92	0.14	0.52	15.62
[45]	2.70	1.30	1.30	61.0	8.70	0.11	12.0	2.8	2.70	-	18.0
[46]	0.98	1.51	1.19	44.81	3.81	0.288	6.89	1.64	1.07	1.72	35.9
[47]	9.34	1.18	1.98	49	2.66	-	25.8	-	1.02	3.29	-
[39]	34	13.5	5.0	16.5	3.1	-	5.5	1.5	-	-	14.3
[42]	7.32	0.4	-	2.73	2.89	-	14.5	-	-	2.88	-
[36]	38.29	12.87	7.64	14.30	1.94	-	3.28	-	-	-	-

is determined by the presence of the three oxides of silicon, aluminium, and iron [21]. Table 1 indicates that depending on its chemical composition, WA can be classified as either class F or C pozzolana, with some WA perhaps falling below the minimum standards [38]. According to the research presented by Tamanna et al. [22], the chemical composition of WA varies depending on wood source and method of combustion. However, the presence of a significant amount of K<sub>2</sub>O in all the WA presented in table 1 demonstrates that WA can be used as an alkaline source in geopolymer concrete production.

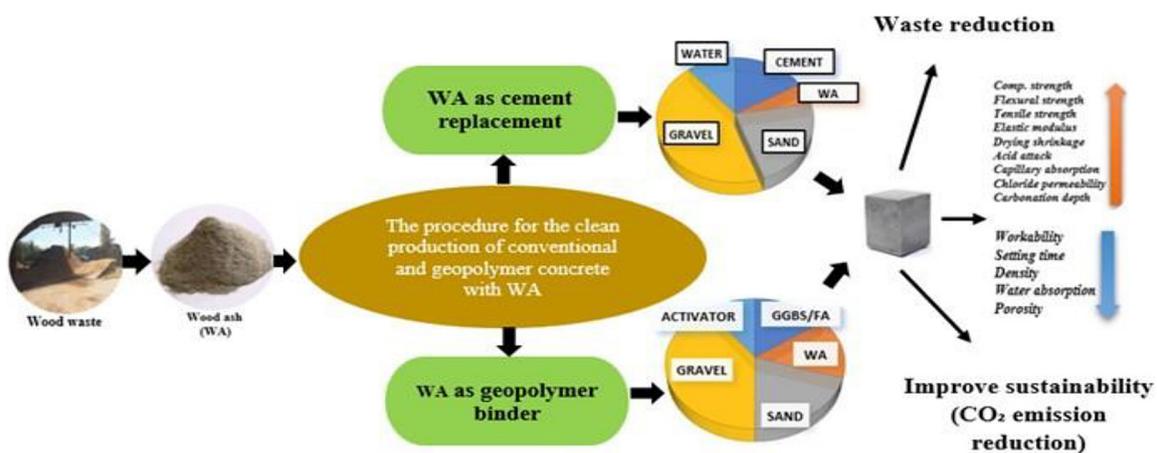
### PROCEDURE FOR CLEAN PRODUCTION OF CONVENTIONAL AND GEOPOLYMER CONCRETE WITH WA

The process for the clean production of both conventional concrete and geopolymer concrete with WA is presented in Figure 2.

### EFFECT OF WOOD ASH ON CONVENTIONAL MORTAR/CONCRETE

#### Rheological properties

Cheah and Ramli [43] investigated the properties of cement paste produced with high calcium wood ash (HCWA) and densified silica fume (DSF) as cement supplement. It was noted that the addition of WA led to high water demand of the cement paste to obtain a standard consistency. It was also reported that when WA is used as a partial replacement of cement in foam concrete, the water requirement of the mixture rises as the percentage dosage rises, similarly, a reduction in the density of the mixture was noted [48]. Fluidised bed combustion fly ashes (FBCFAs) of wood and peat were used by Rissanen et al. [49] to partly replace cement in the mortar at 10, 20 and 40% replacement levels. The research outcome indicated that the FBCFAs mortar required a high dosage of superplasticiser to achieve similar workability



**Figure 2.** Procedure for the clean production of conventional and geopolymer concrete with WA

with control mortar. In a recent study by Carevic et al. [50], noted that an increase in the percentage of WA was associated with a loss in workability, which led to the addition of mixing water with an average of 10% for cement paste. Similar trend was observed in the cement mortar, and the decrease in consistency was 8, 16 and 32% for 5, 10 and 15% WA content. They also noticed a loss in workability of 19, 38 and 44%. This finding is proved by the work of [51], where WA was reported to absorb the mixing water, to maintain the same slump with the control specimens, more plasticiser was added as the content of the WA increased as shown in Table 2.

The influence of WA on the rheological properties of mortar/concrete can clearly be concluded as loss on workability and delay in setting time. The loss on workability due to addition of WA to replace cement can be related to the hygroscopic properties of WA and the high irregularly shape of the ash particles [52], these findings were also confirmed by Santek Bajto et al. [53]. Similarly, Carevic et al. [50] attributed the increase in water requirement due to WA content to morphology, high porosity, high specific surface area, high LOI and high CaO content of the WA. The delayed in setting time was also credited to low content pozzolanic oxides and high LOI of the WA [54]. Similarly, Hussain et al. [55] investigated the setting time of concrete produced with WA as partial cement replacement from 0–60%. It was noted that both initial and final setting time increased with an increase in the WA content, this was attributed to the less reactivity of the WA compared to OPC.

Nader et al. [56] studied the properties of cement mixes using wood bottom ash as cement replacement from 0–50% replacement level. The study revealed an increase in w/c ratio of the mixes which was credited to the higher specific surface area of the WA compared to that of OPC. It was also revealed that the initial setting time of the mixes drops as the percentage of WA increases, this was attributed to the higher content of sodium oxide in the WA compared to OPC which accelerate the initial setting time. On the contrary, the final setting time of the mixes were observed to increase, this according to the author was due to the higher content of phosphorous pentoxide in the WA which contribute to delay the final setting time. Ristic et al. [57] led a research on properties of self-compacting concrete produced with WA to replace coal FA from 0–40%. The fresh properties investigated revealed that the increase of WA in the

mix increase the requirement of super plasticizer to obtain the target slump. Similarly, the fresh density and filling ability of the concrete were observed to decrease with the increase of WA content.

Studies reviewed show that WA affects the rheological properties of concrete. Being a hydroscopic material, it absorbs water, increasing the concrete’s water demand. For all mixes with WA, w/c ratio increases as WA content increases, probably due to high porosity, specific surface area, LOI, and CaO content. Therefore, to maintain a desired slump when WA is used as cement replacement, a superplasticizer or additional water is required.

### Mechanical properties

WA was reported to improve the micro-structure and mechanical properties of mortar/concrete. Several researchers employed the use of WA as supplementary cementitious material (SCM) in concrete and results obtained shows its ability to improve the concrete quality, hence can be utilized to replace OPC at certain percentage. Percentage replacement, properties investigate and findings of several studies on its utilization as cement replacement are shown in Table 3.

### Compressive strength

Many researchers as presented in Table 2 reported similar findings which shows that the utilization of WA to partially replace of OPC in mortar/concrete production enhance the compressive strength as compared to 100% cement concrete. The percentage replacement of OPC with WA in most of the studies ranges between 5–70% by weight of cement, were 5–15% WA were mostly recommended as optimum percentage replacement by most of the researchers. Carevic et al. [50] justified that the strength increase was attributed to the pozzolanic activity of the WA. This reaction occurs between the SiO<sub>2</sub> from the WA and the portlandite [Ca(OH)<sub>2</sub>] from the cement

**Table 2.** Percentage replacement of cement and slump [51]

WA content (%)	Admixture content (% of cement)	Slump
0	0.00	48
10	0.60	52
15	0.62	55
20	0.66	54
25	0.70	56

**Table 3.** Effect of WA on mechanical properties of mortar/concrete

Author(s)	Replacement level of WA investigated	Properties investigated	Findings	Remarks
[43]	0–16% high calcium wood ash (HCWA) with 7.5% densified silica fume (DSF). 8%HCWA + 7.5%DSF was recommended as optimum.	Compressive strength	49.5–54.1 MPa for 0–8% HCWA at 28 days.	A rise in compressive strength was observed up to 8% HCWA + 7.5% DSF replacement level which was attributed to the dominating dilution effect of cement content in the mixture with HCWA and DSF.
[25]	0–25% HCWA at 5% incremental level. 15% was recommended optimum.	Compressive strength	28- and 90-days ranges between 38.99 – 44.90 MPa, and 43.77–49.55 MPa, respectively.	All specimens with WA possessed lower strength compared to control up to 28 days. At 90 days 15%WA specimens possessed the highest strength probably due to prolong pozzolanic effect of the WA. Specimens with WA 5 and 10% possessed highest flexural strength compared to reference specimen at both 28 and 90 days, this was attributed to fine particles of WA which played a role of filler within the pores of the mortar, hence producing a denser material that led to a higher flexural strength.
		Flexural strength	28- and 90-days flexural strength ranges between 6.86–8.90 MPa, and 7.69–9.73 MPa, respectively.	
[58]	0–30% WA at 5% incremental level. 10% was recommended as optimum.	Compressive strength	Compressive strength at 28 and 90 days was recorded around 49–38 MPa and 54.5–40 MPa, for 0–30% WA.	For all replacement levels a linear decrease in both strengths were recorded compared to control specimens likely due to the fact that WA act like a filler in the matrix than as a binder.
		Tensile strength	Tensile strength at 28 and 90 days was recorded around 4.8–3.8 MPa and 5.4–3.6 MPa, for 0–30% WA.	
[59]	0–10% WA at 5% incremental level. 10% was recommended as optimum.	Compressive strength	53.4, 62.4, and 57.4 MPa for 0, 5, and 10% WA at 365 days.	The prolong strength development was possibly due to the function of the WA as a filler in cement base material
		Flexural strength	8.0, 9.4, and 8.9 MPa for 0, 5, and 10% WA at 365 days	
[44]	0–20% WA at 10% incremental level. 10% was recommended as optimum.	Compressive strength	90 days compressive strength: 59, 61, and 60 MPa for 0, 10, and 20% WA specimens.	At 90 days of curing 10% WA specimen possessed the highest strength followed by 20% than the control specimens. Comparable flexural strength results were obtained for both replacement levels at 90 days. The strength development was attributed to the pozzolanic effect of WA at prolong curing period.
		Flexural strength	90 days flexural strength: 8, 7.8, and 7.8MPa	
[37]	0, 5, 10, 15, 18, and 20%	Compressive strength	28 days compressive strength: 36.8–31.7 MPa for 0–20% WA.	At 0.4 W/C a reduction in both strengths for all WA specimens was noted, this was probably due to the fact that the WA performs as a filler in the cement medium and not as a binder, which increase the surface area of filler material that required to be bounded by cement.
		Split tensile strength	28 days split tensile strength: 3.51–2.53 MPa	
		Flexural strength	28 days flexural strength: 5.77–4.97 MPa	
[48]	0–20% across 4 different densities in foam concrete. The study recommended 10% as optimum.	Compressive strength	7–14.5 MPa for control specimens across all densities. 6–13.0 MPa for 10% WA	At 10% WA inclusion across all densities the strengths were recorded higher than 20% WA specimens.
		Modulus of elasticity	3.0–11 MPa for 20% WA 2860–6160 MPa for control specimens 35% drop was recorded for 20% WA specimens.	
[56]	0–50% at 10% incremental level. The study recommended up to 20% as optimum	Compressive strength	25.1–1.7 MPa at 28 days	The study suggested 20% of cement can be replaced with WA for an average strength mortar of about 14 MPa at 28 days.
		Split tensile strength	2.1–0.8 MPa at 28 days	
		Flexural strength	10.9–1.3 MPa at 28 days	
		Modulus of elasticity	32860–12617 MPa for 0–30% at 28 days	
[36]	0–15% WA and seashell powder (SSP) at 5% incremental level. 10% WA+SSP was recommended.	Compressive strength	29.23–33.69 MPa for 0–10% at 28 days.	At 0.45 W/C the concrete specimens with 10% WA + SSP content possessed the highest compressive, tensile, and flexural strengths, respectively. This was credited to the pozzolanic properties of WA and SSP.
		Split tensile strength	2.64–2.97 MPa for 0–10% at 28 days	
		Flexural strength	4.36–4.69 MPa for 0–10% at 28 days	

Table 3. Cont.

[50]	5–15% at 5% incremental level. 5% was recommended.	Compressive strength	48–52 MPa and 55– 62 MPa for 0–5% at 28 and 90 days, respectively.	Rise in strength was attributed to the pozzolanic oxides from the WA.
[60]	0–15%WA at 5% incremental level	Compressive strength	42.7, 41.3, and 36.3 for 0, 5, and 10% WA at 28 days 47.5, 46.9, and 43.5 MPa for 0, 5, and 10% WA at 56 days	At a mix ratio of 1:1:2, the specimens with 5% WA level possessed almost similar strength with control specimens at both 28 and 56 days, respectively.
[51]	0–25%WA. 10% was recommended as optimum	Compressive strength	34.17–22 MPa at 28 days	At a fixed 0.50 W/C, WA increased was observed to reduce the compressive strength in comparison with reference specimens. The highest strength of 24.71 MPa among the WA samples was attained by 10% WA which was closed to the designed strength of M25 grade. The strength enhancement was credited to pozzolanic effect of the WA.
[61]	0–70%WA at 10% incremental level. Up to 20% recommended.	Compressive strength	Approximately 59 MPa for control specimens, and 68–15 MPa for 10–70% at 28 days	At varying W/C ratio from 0.5–0.67 (70% WA) due to hydroscopic properties of WA, it was observed that specimens with 10 and 20% WA possessed a strength higher than the control specimens. Possibly due to the pozzolanic properties if the WA.
		Flexural strength	Approximately 7.5M Pa for control specimens, and 9–3.5 MPa for 10–70% at 28 days	
[62]	0–20% at 5% incremental level. 15% WA was recommended as optimum.	Compressive strength	Approximately 43 MPa for 0%WA. 44, 46, and 43 MPa for 10, 15, and 20% WA at 28 days.	At a fixed 0.4 W/C it was observed for 15%WA replacement there was an increment in the 28 days compressive strength of about 8.24% compared to control, similarly, the flexural strength was observed to follow same trend where 7% increment was noticed at 15% replacement level compared to control.
		Flexural strength	Approximately 4.8, 4.9, 5.2, and 4.6 MPa for 0–20% WA at 28 days	
[53]	15% replacement level for 5 different WA sources (CM1 – CM5).	Compressive strength	20.2, 13.7, 14.2, 16.1, and 13.5 MPa were observed for specimens from CM1 – CM5 compared to control (CM0) with 2.74 MPa at 1 day. 54.8, 39.8, 28.6, 28.7, 36.2, and 42.5MPa for CM0 – CM5 specimens at 28 days.	At a constant W/C ratio of 0.44, the early days strength of WA specimens was seen to be low by 26 to 56% CM1 – CM5 samples compared to reference specimen probably due to heat of hydration. At 28 days all WA specimens possessed lower strength compared to reference specimens. This finding confirmed a decrease in strength when WA is used to replace cement.
[63]	10% replacement level for 2 different sources of WA (WA1 and WA2).	Compressive strength	At 90 days, 74.1, 68.9, and 66.7 MPa were recorded for control, WA1, and WA2 specimens. At 365 days, 77, 70.5, and 69.1 MPa for control, WA1, and WA2 specimens.	The strength of the 2 WA samples were seen to possessed lower strength compared to control samples at both ages of hydration. Among the WA samples used, WA1 samples possessed higher strength compared to WA2, possibly due to differences in their chemical composition. WA1 was seen to have more CaO and lower LOI compared to WA2.
[64]	0–45%WA from 3 different sources of WA (F4, F5, and F6)	Compressive strength	43.3–31.9 MPa for F4 15–30% at 28 days. F5 15, 30, and 45% 28 days strength was 45.3, 37.3, and 30.1 MPa. For F6 5 and 15%, 28 days strength was 48.9 and 54.5 MPa.	It was observed that mixture with F6 WFA possessed higher 28 days strength compared to control and specimens with F4 and F5 specimens. This was credited to the WA particle size distribution which is comparable to that of OPC. Other WA (F4 and F5) was coarser. The finer particle of F6 WA increase cohesiveness which resulted in a denser structure.
[57]	10–40% replacing fly ash (FA) in self-compacting concrete (SCC). Up to 30% was recommended as FA replacement in SCC.	Compressive strength	Approximately 34–25 MPa for 0–40% WA specimens at 2 days. At 28 days, 58 MPa was attained by control specimens, 59–49 MPa for 10–40% WA specimens.	Lower early strength was observed for all WA specimens compared to reference specimen. At later ages of curing 10% WA specimens attained the highest strength which was attributed to internal curing provided by WA and higher compactness of concrete as a result of less amount of free water. Flexural strength was observed to decrease with WA inclusion at both 28 and 90 days. For tensile strength specimens with 10% WA was higher than the control by 3.3% and 4.3% at both 28 and 90 days. All WA specimens possessed lower 28 days modulus of elasticity compared to control specimens.
		Flexural strength	5.8–4.9 MPa for 0–40% WA at 28 days. 7.5–6.1 MPa for 0–40% at 90 days.	
		Tensile strength	Approximately 4 MPa and 4.1 MPa for 0 and 10% specimens at 28 days. At 90 days 4.7 and 4.9MPa for 0 and 10% specimens.	
		Modulus of elasticity	29.54 GPa – 24.2 GPa for 0–40% WA	

during curing period of the concrete resulting in formation of larger amount of C-S-H gel that contribute towards densification of microstructure. Fort et al. [61] discovered that up to 20%WA can be used to replace OPC. In their research, they discovered that specimens with 10 and 20% WA possessed higher compressive strength compared to 100% OPC specimens. Similarly, Vijay et al. [62] observed that 15%WA specimens possessed a higher strength compared to reference specimen with about 8.24%. Both studies credited the strength improvement to pozzolanic effect of WA. Gabrijel et al. [64] investigated the effect of three types of WA (F4, F5 and F6) from three different sources. 0–45% replacement level was used in the research. The outcome revealed that F6 15%WA specimens possessed highest 28 days strength of 54.5 MPa compared to control. They attributed the strength enhancement to the finer particle of F6 WA which increase cohesiveness, hence resulted in a denser structure.

Contrastingly, other researchers observed that the inclusion of WA in concrete as cement replacement led to lower compressive strength compared to specimens produced with only OPC. In their study [37], justified that WA performs as a filler in cement medium and not as a binder, this increase the surface area of the filler material required to be bounded by cement. In order to improve the strength properties of WA containing mortar, Cheah and Ramli [43] employed the use of HCWA and DSF to replace OPC. 0–16% HCWA with a fixed 7.5% DSF was used in the study to replace OPC. They observed that 8%HCWA + 7.5%DSF mortar exhibited the highest strength of 54.1 MPa at 28 days which was credited to the pozzolanic effect of both HCWA and DSF. Similarly another investigation on the compressive strength of mortar containing HCWA as OPC replacement from 0–25% was carried out, they discovered that specimens with 15%HCWA possessed a higher strength at 90 days compared to reference specimens, justified the prolong pozzolanic effect of HCWA [25]. Other researchers [44,59] recommended the replacement of OPC with 10%WA. In their studies, highest strength of 62.4 MPa at 28 days and 61 MPa at 90 days were attained both by specimens with 10%WA. Garcia and Sousa-Coutinho [59] justified that the prolong strength increase was likely as a result of the prolong pozzolanic activity of the WA.

Rollakanti et al. [39] combined the use of WA and seashell powder (SSP) to replace OPC at

0–15%. The investigation revealed that 10%WA + SSP specimens possessed the highest 28 days compressive strength of 33.69 MPa. Similarly Ristic et al. [57] investigated the inclusion of WA at 0–40% to replace FA in self-compacting concrete (SCC). They observed that specimens with 10%WA possessed the highest strength of 59 MPa at 28 days. The study recommended that WA can be used to replace FA up to 30% in SCC due to its pozzolanic properties. Generally, the inclusion of WA at higher level in mortar/concrete led to strength reduction. However, other studies shows that WA inclusion at lower level (up to 10%) can produce a structural grade concrete with adequate strength.

### *Flexural strength*

Cheah and Ramli [25] examined the effect of OPC replacement with HCWA on flexural strength of cement mortar. HCWA was used to replace OPC from 0–25%. The result of the investigation revealed that the highest flexural strength was attained by specimens with 5 and 10% HCWA at both 28 and 90 days of curing. The increased flexural strength was attributed to the finer HCWA particles, which serve as a filler within the pores between the cement and aggregate. This led to the development of a denser material which directly influenced the flexural strength. On a similar note, Garcia and Sousa-Coutinho [59] investigated the flexural strength of a mortar produced with WA at 0, 5, and 10% replacement level. Results of the investigation shows that the flexural strength of all specimens with WA was lower than the control at 28 and 90 days, respectively. At a prolong curing period of 365 days, both 5 and 10%WA specimens possessed higher strength compared to control by 8 and 11%, respectively. The later strength development was probably due to the function of WA as a filler in the cement material and the pozzolanic effect. Similar result was obtained by Ramos et al. [44] where the 90 days flexural strength of WA specimens was comparable to that of the control specimens.

Contrastingly, other researchers observed a decrease in flexural strength of WA specimens at all curing periods compared to reference specimens [37, 56, 57]. Rollakanti et al. [36] tried to improve the properties of cement mortar by combining WA and SSP to replace OPC. A visible increase in the flexural strength was noted for 10%WA + SSP specimens compared to control, 5, and 15%WA + SSP specimens. Similar increase in flexural strength was observed at 28 days hydration period

for 10 and 15%WA inclusion [61,62]. The studies reviewed revealed that the flexural strength of mortar with WA at up to 10% replacement level was seen to be improved, most likely due to the micro filler of fines particles of WA. Therefore, for acceptable flexural strength, WA can replace cement at lower replacement level.

#### *Split tensile strength*

Ghorpade [58] reported a reduction in the tensile strength of a concrete produced with the inclusion of WA as a partial replacement of OPC from 0–30% at 5% incremental level. A decline in the strength was recorded at both 28 and 90 days for all percentage replacement. Other researchers observed similar reduction in 28 days tensile strength [37, 56]. The strength decrease was probably due to the fact that WA perform more as filler than binder in the mixture which increase the surface area of filler material required to be bound by cement. This reduced the cement in the mixture with proportion to filler material. Contrastingly, other researchers reported an increase in tensile strength with WA inclusion at 10% by weight of cement. They credited the strength improvement to the pozzolanic effect of the WA [36, 57].

#### **Durability properties**

Fusade et al. [47] studied the drying shrinkage of two sets of mortar prepared with natural hydraulic lime (NHL) and air lime (AL). WA was used as fine aggregate replacement at 0, 10, 20, 30, 40, 70 and 100%, respectively. It was observed that the 28 days drying shrinkage increases as the WA content increased in the mixture for both mortars. This was due to the fact that the inclusion of WA introduced more fine material into the mixture. Drying shrinkage was reported to be influenced by aggregate size in a mixture. Usually, coarse aggregates increase the stability of mortar compared to fine material which increase the possibility of higher shrinkage. Similarly, Ristic et al. [57] utilizes WA to replace FA in SCC. The drying shrinkage result indicated that the WA specimens has higher drying shrinkage compared to 100% OPC specimens which was possibly due to the loss of water in the WA specimens due to the coarse capillary pores with water during water curing. Contrastingly, Carevic et al. [50] observed a reduction in the drying shrinkage when WA was used to replace OPC in a cement mortar. A drying

shrinkage observed at 365 days shows that the inclusion of WA at 5, 10, and 15% decreased the mortar's drying shrinkage by 20, 21, and 24% compared to control specimens. They noted that the decrease in the drying shrinkage was related to the content of free CaO in WA.

Other durability properties like water absorption and porosity were also investigated by several researchers. Hussain et al. [55] examined the water absorption of a cement mortar. WA was used to replace OPC in the mixture from 0 – 60%. A noticeable increase in the percentage of water absorption was recorded for all the WA specimen compared to control specimens. WA is identified as hydrophilic. This makes specimens with WA to be more water absorbent compared to reference specimens with 100% WA. Similarly, Fusade et al. [47] assessed the water absorption of NHL and AL mortar produced with WA as cement replacement. They observed that both NHL and AL mortars with WA have higher water absorption compared to control specimens, this was possibly due to the hydroscopic nature of WA which tends to absorb and hold more water. On a similar note, Rissanen et al. [49] studied the effect of WA from two different sources on the porosity and water absorption of cement mortar. WA was used to replace cement at 10, 20, and 40%. In both NHL and AL mortars, it was observed that WA inclusion led to an increase in porosity. Similar trend was observed in the water absorption test where the percentage water absorption for 20 and 40%WA specimens were relatively higher than that of the control specimens. This was attributed to the formation of micro pores in the mortar with WA. Other researchers also reported similar increase in porosity and water absorption as WA content increased [53, 62, 64].

Contrastingly, Carevic et al. [50] investigated the capillary absorption of cement mortar containing WA as cement replacement at 5, 10, and 15% by weight of cement. A reduction of 6.04 and 3.25% in the capillary absorption were noticed for 5 and 10%WA specimens. Further increase of WA to 15% increases the capillary absorption with about 2.27% compared to control specimens. Similarly, Kannan and Priya [65] examined the effect of WA on water absorption of high strength concrete (HSC). OPC was replaced with WA from 0–40%. The water absorption was observed to decrease up to 20% replacement level compared to reference specimens. A gradual increase was observed beyond 20% replacement

level. However, Cheah and Ramli [43] tried to improve the durability properties of WA containing mortar. A chloride profiling test was carried out to investigate the durability of cement mortar produced with HCWA and DSF as partial cement replacement. The specimens were subjected to salt water with a 4% concentration of sodium chloride (NaCl). The specimens were immersed in the salt water after 28 days of water curing. It was observed that all specimens with HCWA content possessed lower average chloride content compared to control specimens. 4%HCWA + 7.5%DSF were noticed to have the lowest chloride content of 0.07%. They attributed the lower chloride to the refinement of micro pores in the HCWA + DSF specimens. Contrastingly, Garcia and Sousa-Coutinho [59] reported WA specimens possessed a higher chloride permeability compared to 100% OPC specimens.

Other durability properties like carbonation test and acid resistance of WA containing mortar/concrete were investigated. Garcia and Sousa-Coutinho [59] investigated the carbonation of cement mortar using carbonation chamber with 5% CO<sub>2</sub> with 65% relative humidity. The result of the carbonation test at 245 days revealed that the control specimens possessed 7.0 mm. A decrease in the carbonation depth of 4.3 mm was noted in 5%WA specimens, 10%WA specimens were recorded the highest carbonation depth of 8.3mm. On the other hand, Ramos et al. [44] reported an increase in the carbonation depth as the WA content increase in the mixture. This follows the trend of pozzolanic materials, which may be credited to calcium hydroxide (CaOH) reduction, this led to pH reduction. An average depth of 3.33 and 4.60 were observed for 10 and 20%WA specimens compared to 2.62 of the control specimen. Hussain et al. [55] investigated the durability of concrete with WA as OPC replacement against acid attack. The concentration of acid used in the investigation was 5%. The specimens were cured for 28 days in water before being transferred to acidic environment for 60 days. At 20% WA inclusion, the weight and strength loss of the samples were less than that of the control specimens. However, WA inclusion beyond 20% show a loss in compressive strength compared to 100% OPC specimen due to the greater mass loss of the specimens with WA content beyond 20%.

The inclusion of WA in mortar/concrete was seen to enhance their durability properties to some extent. WA containing mixes showed a

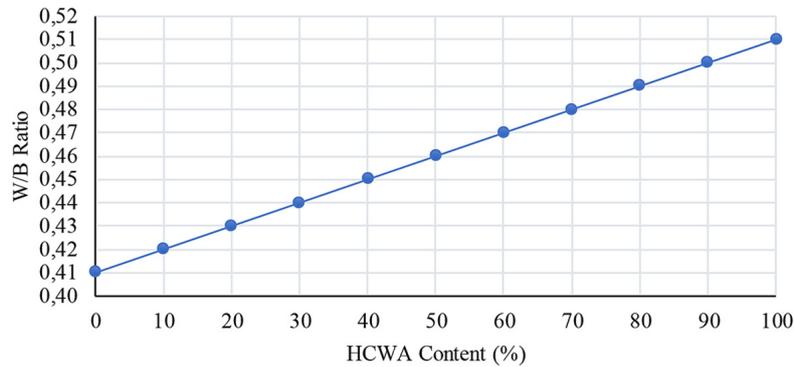
reduction in drying shrinkage at lower level of OPC replacement. When WA was used to replace fine aggregate, WA was observed to have negative impact on the drying shrinkage. Other durability properties such as acid attack, capillary absorption, chloride permeability, and carbonation depth were noticed to be improved by WA inclusion at up to 10% replacement level. On the other hand, water absorption and porosity were slightly affected by WA inclusion possibly due to the hygroscopic properties of the WA. For an enhanced durability properties, several researchers recommended up to 10% replacement of OPC with WA in both mortar and concrete production.

## EFFECT OF WOOD ASH ON GEOPOLYMER MORTAR/CONCRETE

### Fresh properties

Cheah and Samsudin [66] investigate the hybridisation of HCWA and GGBS in geopolymer mortar fabrication. HCWA was used to replace GGBS up to 100% at a 10% increment level. It was noted that the increase in HCWA led to the increase in the surface area, which requires additional mixing water to take care of it as depicted in Figure 3.

Another study by Cheah et al. [11] researched the ternary blend of geopolymer mortar with GGBS, HCWA and PFA. The ratio of GGBS:HCWA was fixed at 80:20. PFA was then included into the mix, replacing the binder up to 100% at a 10% step increment level. Sodium hydroxide (NaOH) and sodium silicate (Na<sub>2</sub>SiO<sub>3</sub>) were used as alkaline activators at a lower level with liquid binder ratio, alkaline activator ratio and concentrations of 0.11, 1.2 and 12M, respectively. It was noted that an increase in the percentage replacement of the binder with PFA led to reducing the water demand to attend a standard consistency which was 258 kg/m<sup>2</sup> at 0% PFA and 160kg/m<sup>2</sup> at 100% PFA, indicating that the high of amount of GGBS and HCWA require high water content due to their large surface area. The initial and final setting times of 20 and 90 min were observed for 0% PFA mixture as well as 280 and 360 min for 100% PFA mixtures. These rapid-setting properties were linked to the high calcium content of the binders and the hygroscopic nature of the HCWA. In similar research by Cheah et al. [67], HCWA was used as a supplement of PFA to fabricate a geopolymer mortar block with a small amount of



**Fig. 3.** Water-binder ratio on mix proportion [66]

sodium silicate. The percentage replacement used in the study was up to 100% replacement level at 10% increment. The standard consistency of the geopolymer block was reported to be affected by the increase in the percentage replacement of PFA with HCWA, which was credited to the angular shape of the HCWA that trapped water between particle spaces. The same phenomena were observed in another work of the researcher [11]. It was reported that HCWA content affect setting time of geopolymer. A mixture with 30% FA and 70% HCWA exhibits the lowest initial and final setting times of 30 and 240 minutes, respectively. The mixtures with the highest initial and final setting time were the control mixture with 100% FA, 80% FA, and 60% HCWA and 100% HCWA. It was noticed that the delay in setting time of the high PFA mixtures was due to the lower reactivity of the PFA at the early stage because of the low alkaline in the matrix.

Abdulkareem et al. [45] examined the strength and porosity of PFA-WA geopolymer mortars. They noticed that the rise in the percentage content of WA to replace PFA, the higher the superplasticiser needed to maintain the required mortar flow. Comparable outcomes were reported in similar study [68]. They also reported that the initial and final setting time of 100% PFA geopolymer mortar at room temperature was 290 and 410 min, respectively. A reduction in both the setting time was observed with an increase in the WA content in the mixture. At 10% WA, the initial setting time of 210 min was observed, the final setting time followed the same pattern. They attributed the decline in both initial and final setting times with increased WA content to the WA's high surface area, LOI, and hygroscopic characteristic. They also noted that the high CaO component in the WA contributes to the blended mixes setting time

being shortened compared to the control. Arunkumar et al. [69] investigates the inclusion of WA in the production of geopolymer concrete. WA was used in the study to replace PFA from 0–100% at 10% replacement increment. The study revealed an increase in water requirement from 0.38 to 0.49 of the mixes in order to attain a consistency. Similarly, both the initial and final setting time of the concrete were found to decrease with an increase in the WA content which was attributed to the presence of calcium in the WA.

It can be concluded that the rheological properties of geopolymer concrete are highly influenced by the physical properties of the WA. A reduction in both initial and final setting time was observed probably due to the hygroscopic nature of the WA. Similarly, The water demand and workability of the geopolymer mortar/concrete increases with the increase of WA which may lead to superplasticizer or additional water requirement in order to obtain a desired workability.

### Mechanical properties

The mechanical properties of geopolymer concrete/mortar can be improved by including WA in the geopolymer matrix. WA is reported to have sufficient content of  $K_2O$  ( $\pm 12\%$ ), this arcanite mineral dissolved to form potassium hydroxide (KOH) when the WA is mixed with water, the highly alkaline minerals play a role as a dissolution agent which dissolve the aluminosilicate compounds in geopolymer binder such as PFA, GGBS, POFA and so on which undergoes geopolymerization with the  $K^+$  ions to form K-A-S-H gel [26]. Cheah and Samsudin [69] studied the strength properties of hybrid GGBS-HCWA geopolymer mortar. It was noticed that the geopolymer mortar's strength increased with the addition of HCWA to replace

the GGBS up to 30%. The 30% HCWA content proved to be the optimum content with about 9.3 and 12.3 MPa at 7 and 28 days, respectively, as shown in Figure 4 below. The strength development was attributed to the alkalinity of the HCWA, which triggered the dissolution of aluminosilicate materials present in the GGBS, hence promoting the early strength development.

In a similar study with the hybridisation of FA and HCWA at a varying W/B ratios of 0.3 and 0.35 to produce low alkalinity geopolymer block, Cheah et al. [70] observed an enhancement in the compressive strength of the geopolymer mortar block with the increase in the HCWA content. However, specimens with a 0.3 W/B ratio exhibit higher strength. At 0.3 water binder ratio, the 28 days highest strengths of 17.9 MPa was achieved by 60HCWA:40FA specimens. The flexural strength and modulus of elasticity result was noticed to follow same trend with 0.3 W/B specimens possessing the highest strength compared

with 0.35 W/B specimens. For all the percentage replacement, 60HCWA:40FA specimens possessed the highest strength, as clearly observed from Figure 5.

Cheah et al. [74] investigate the strength of geopolymers produced with the blending of three industrial bye products: HCWA, PFA, and GGBS, using a lower level of alkaline activator. The 28 days strength development was observed for the optimum mixture M50 (50%PFA replacing the binder in the mix, which was 80%GGBS and 20%HCWA) was 36.56 MPa. The early strength development was credited to the higher dissolution of amorphous aluminosilicate materials and the polysialate phase precipitation by incorporating GGBS and HCWA. At the prolonged duration of curing, the optimum mixture shifted to M80 with 42.94 and 49.6 MPa compared to that of M50, which possessed 39 and 45 MPa both at 56 and 90 days, respectively. This later age strength development of higher PFA content samples was

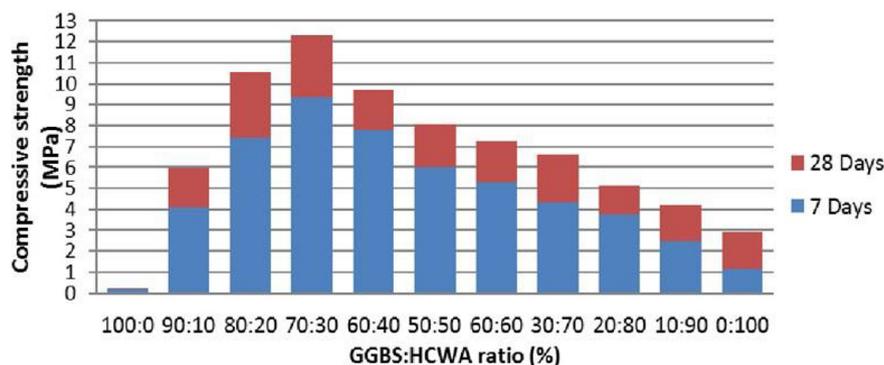


Fig. 4. Comp. strength result of GGBS-HCWA geopolymer mortar [66]

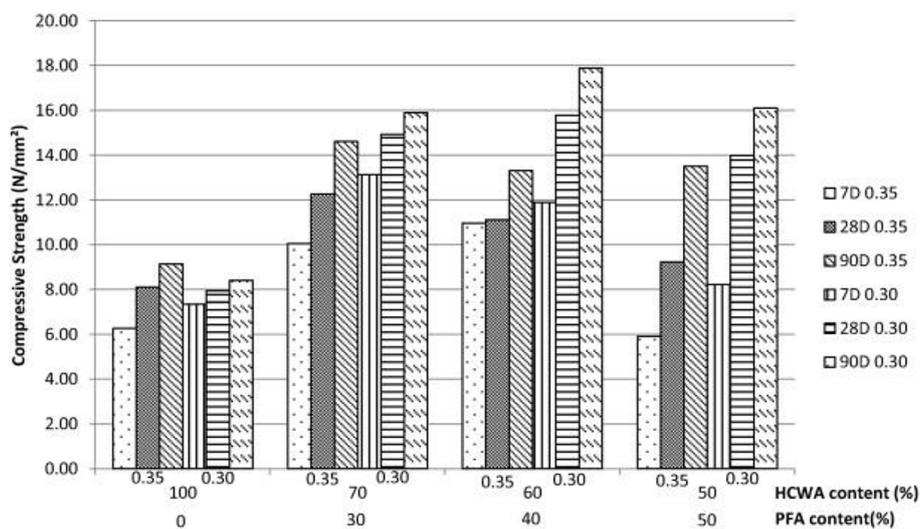


Fig. 5. Compressive strength of HCWA-PFA geopolymer mortars [70]

attributed to the higher dissolution of amorphous aluminosilicate from PFA, which only dissolved at a prolonged period when cured at ambient temperature. Similar relationship to compressive strength was observed in the flexural strength. An increase of 16.36–68.24% was noticed for 10–80% PFA content mixes compared to control. The strength gain in flexure was attributed to bonding strength enhancement due to pores filling the geopolymer matrix and aggregate interface zone by C-A-S-H minerals. For the dynamic modulus of elasticity and UPV test, it was observed that M80 possessed the highest MOE with 33.0, 33.5 and 35.2 for 28, 56 and 90 days, respectively. All mixes had a higher rate of UPV of roughly 90–95% at 7 days, this was attributed to the denser mortar structure formed by the early and rapid geopolymerization. The research recommends that a promising hybrid geopolymer mortar be produced with PFA inclusion at 40–60% replacement level of the binder. Cheah et al. [67] studied the long term mechanical properties of cementless block using HCWA as partial replacement of PFA up to 100% replacement at 10% step increment with a low dosage of sodium silicate. At the long term curing of 365 days, it was observed that 30%HCWA mortar blocks exhibited the highest strength in both compression and flexure. The constant trend was observed in the UPV test, where 40, 50 and 60%HCWA mortars exhibited high UPV at both curing periods, this resulted from the creation of several geopolymeric product phases that led to the formation of the denser microstructure of the mortar.

In another study on the properties of self-activating geopolymer mortar, Ban et al. [29] studied the effect of PFA substitution with HCWA at a higher percentage level of 50–100%. The study's outcome revealed that the highest compressive strength was attained by 50 and 60% HCWA samples at 28 days curing period with 7.8 and 7.7 MPa, respectively. The flexural strength result was observed to follow same pattern. Also, for the non-destructive test using UPV, 60% HCWA specimens exhibited the highest UPV value of 3120 m/s. Similarly, the dynamic modulus of elasticity of 50%HCWA specimens possessed the highest MOE of 20.97 GPa. It was expected that the early strength development was as a result of the geopolymer product of K-A-S-H formation and the HCWA hydraulic reaction. The research recommended including 50–60% HCWA in PFA based self-activating geopolymer mortar for excellent mechanical properties. Abdulkareem et

al. [48] investigated the effect of WA inclusion in PFA geopolymer. In the study, WA was used to replace PFA at 5, 15 and 25% replacement level, NaOH and Na<sub>2</sub>SiO<sub>3</sub> were used as an alkaline activator at 0.50 liquid binder ratio. It was observed that the specimen with 5% WA content had the highest compressive strength of 61.32Mpa. The continued development of N-A-S-H, K-A-S-H, and C-S-A-H geopolymeric products was linked to the increase in strength. In a similar study, Abdulkareem et al. [68] investigated the strength of blended geopolymer using WA as a partial replacement of PFA. The 100%PFA (control) samples possessed 56Mpa at 28 days, it was observed that the inclusion of WA in the mixture at 10% replacement level shows a noticeable increase in the strength compared to the control specimens. The same trend with the compressive strength was observed for flexural strength at 10 and 20% replacement level, which possessed 137 and 117% above than the reference samples at 28 days, the study recommends 10% as optimum content.

To optimise the replacement level of WA in FA geopolymer concrete, Arunkumar et al. [45] examined the performances of geopolymer concrete made with WA as a partial substitute for PFA at 10–100% replacement level with NaOH + Na<sub>2</sub>SiO<sub>3</sub> alkaline activators. The 30% replacement level specimens were observed to possess the highest compressive strength of 35 MPa at 28 days, compared to control samples with 31 MPa. The study recommends 30% as the optimum content of WA in FA geopolymer concrete. In a similar study, Arunkumar et al. [69] investigate the properties of geopolymer concrete with WA as partial replacement of PFA from 0% to 100%. The modulus of elasticity, compressive, and flexural strength of the concrete were revealed to be higher at 30% replacement compared to control specimens of 100% PFA. This was credited to the formation of C-A-S-H gel in the matrix which contributed to the pore filling of the geopolymer matrix. The study recommended 30% WA as partial replacement of PFA in geopolymer concrete production. Similar studies was conducted by Owaid et al. [71] where 25% WA was recommended as optimum percentage replacement of PFA in geopolymer concrete production.

The utilization of WA as a binder in geopolymer mortar at up to 30% replacement of either PFA or GGBS was observed to have a positive impact on the mechanical properties which was attributed to the high alkalinity of the WA that

**Table 4.** Comparison of various strengths of geopolymer mortar/concrete with WA with respect to conventional concrete

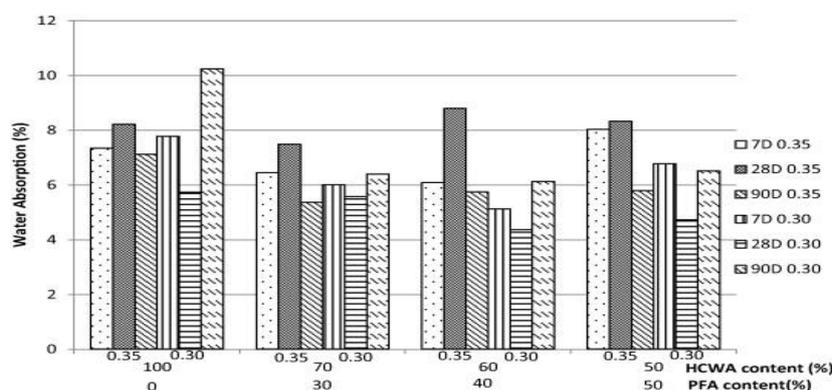
Type of mortar/concrete	Optimum WA (%)	Compressive strength at 28 days (MPa)	References
Conventional	8% HCWA + 7.5% DSF	54.1	[46]
Conventional	15% WA 85% OPC	54.5	[67]
Conventional	10% WA + SSP 90% OPC	33.69	[39]
Conventional	10% WA 90% OPC	59.0	[60]
Conventional	10% WA 90% OPC	62.4	[62]
Geopolymer	30% HCWA 70% GGBS	12.3	[69]
Geopolymer	60% HCWA 40% FA	17.9	[70]
Geopolymer	HCWA: GGBS 20: 80 + 50% PFA	36.56	[74]
Geopolymer	5% WA 95% PFA	61.32	[48]
Geopolymer	50% HCWA 50% PFA	7.8	[29]
Geopolymer	10% WA 90% PFA	58	[71]
Geopolymer	30% WA 70% PFA	35	[45]

triggered the dissolution of aluminosilicate compounds in the binder materials. Therefore, inclusion of WA at up to 30% of the binder material was recommended by many researchers for an enhanced mechanical properties. Table 4 presents the comparison of various strength of geopolymer mortar/concrete as reported in literature.

### Durability properties

Cheah et al. [70] studied the durability properties of low alkalinity geopolymer block produced with FA and HCWA with varying water/binder (W/B) ratios of 3.0 and 0.35, as shown in Figures 6 and 7. For the samples with 0.30 W/B ratio, the addition of FA to replace HCWA at 30, 40, and 50%

reduced the 7 days water absorption by 17.7, 34.2 and 13.0%, respectively. It was observed that specimens with 0.30 w/b ratio possessed lower water absorption than those with a 0.35 W/B ratio at an early age because the degree of polymerisation at an early age is higher within the mix. At a later age, the samples with a 0.30 W/B ratio possessed higher water absorption than the samples with 0.35; this was credited to the fact that 0.30 W/B ratio samples have a higher degree of surface porosity as compared to their counterpart. The 7 days total porosity observed shows a reduction in the porosity of 0.35 W/B ratio samples by 9.1, 13.1 and 16.5% for FA 30, 40 and 50% samples, respectively. The same trend was observed for samples with a W/B ratio of 0.30, which possessed lower total porosity,



**Fig. 6.** Water absorption of HCWA-PFA geopolymer mortars [70]

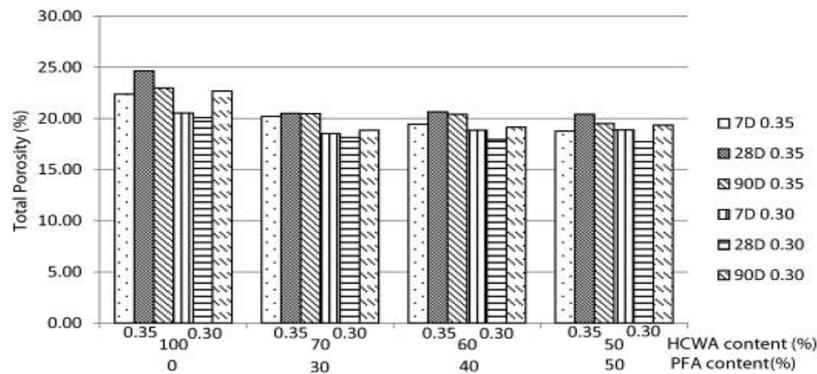


Fig. 7. The total porosity of HCWA-PFA geopolymer [70]

credited to the lower water content of these samples and a higher degree of polycondensation within the mixture, the optimum mixture was noted to be 60%HCWA : 40%FA with a 0.30 W/B.

Ban et al. [26] also studied the effect of FA substitution with HCWA at a higher percentage level of 50–100% at 10% increment to produce self-activating geopolymer mortar. The outcome of the study revealed that 50% of HCWA specimens exhibit excellent durability properties compared to the remaining specimens. In a similar study, Abdulkareem et al. [48] investigates the effect of lower level replacement of FA in chemically activated geopolymer. WA was used to replace FA at 5, 15 and 25% replacement level, NaOH and Na<sub>2</sub>SiO<sub>3</sub> were used as an alkaline activator at 0.50 liquid binder ratio. Durability properties assessed in the study include water absorption and total porosity. It was observed that the samples containing 5 and 15%WA exhibited lower water absorption and total porosity at both 3 and 7 days, respectively, compared to control samples. However, the 5%WA

specimens show less total porosity compared to control samples at 28 days. It was noted that early low water absorption was due to the high content of the geopolymeric reaction, which refined the geopolymer structure. Moreover, at 28 days, the water intrusion on the surface of the geopolymer mortars led to high water absorption compared to control samples, as clearly depicted in figure 8 below. The study recommended 5% as the optimum percentage replacement of FA with WA in the geopolymer.

### SUSTAINABILITY IMPACT OF WOOD ASH IN CONCRETE PRODUCTION

The utilisation of WA in the construction industry may have a beneficial influence on environmental sustainability [72]. The environmental, social, and economic aspects of sustainability were evidently impacted by the incorporation of WA in concrete production. WA incorporation in concrete production may reduce the amount of

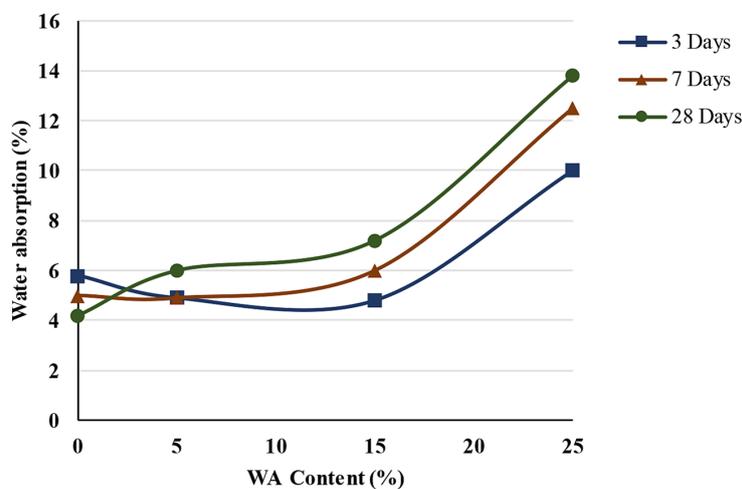


Fig. 8. Water absorption of WA-FA geopolymer mortars [45]

cement required, reducing cement production and improving environmental sustainability [72]. Use of WA in concrete production has the potential to mitigate other environmental effects of waste management disposal by reducing the amount of space needed for disposal and the amount of pollution created by WA's finer materials, which can aggravate respiratory conditions [73,74]. Furthermore, Nodehi and Taghvaei [75] observed that the use of waste materials in the building industry may have various advantages, including cost savings and a reduction in CO<sub>2</sub> emissions associated with the usage of virgin resources.

The environmental issue related to activities from the construction sector includes contamination of air quality majorly because of greenhouse gas emissions arising from cement production. Several studies evaluate the use of WA as cement replacing material, and the result indicated that up to 10–20% of cement could be replaced with WA in both mortar and concrete production as discussed in previous sections. If this is adopted, a significant reduction in the release of CO<sub>2</sub> from cement production will be observed. Similarly, waste generated from biomass energy in the wood industries degrades our environments due to landfilling these wastes. The existence of this ash that affects the quality of air tends to create discomfort to the community nearby. It may cause respiratory health problems to many people residing in the sites of the landfills [20]. The utilisation of this waste in normal and geopolymer concrete will also reduce the quantum of these wastes in the landfill, thereby improving the sustainability of our environment.

The social pillar of sustainability concerns, among others, the healthy living of humans to ensure a healthier and sustainable community. The utilisation of WA in concrete production will greatly reduce the health and social impact caused by the disposal of wood wastes in our environment, which may cause respiratory health problems. Geopolymer technology was proved to be an effective way of utilising waste materials in mortar and concrete production. Although effective, the cost involved in its production makes it unbearable from economic perspective. The contributing factor to the cost of geopolymer concrete is the utilisation of chemical activators such as NaOH and KOH. Ban et al. [26] discover the potentiality of WA as a source of alkaline activator in geopolymer mortar and can eliminate the use of external activator in geopolymer mortar/concrete production. WA can be a promising,

supplementary cementitious material in normal concrete production and an effective binder and source of alkaline in geopolymer concrete production, which may promote the sustainability of the construction sector.

## RESEARCH GAP

The paper revealed the successful utilisation of WA as supplementary cementitious material, although its chemical composition varies due to some factors as highlighted by Cheah and Ramli [20]. However, its significant content of K<sub>2</sub>O ( $\pm 12\%$ ) proved its suitability in the fabrication of geopolymer mortar/concrete, only limited studies were carried out in this area. Moreover, all the studies on WA utilisation in geopolymer mortar/concrete production concentrated on its use as either GGBS or PFA replacement. No studies were conducted on the effect of blending WA with other pozzolanic materials such as POFA in geopolymer mortar/concrete. Similarly, there is no existing study on whether geopolymer concretes produced with WA can be implemented in high-end construction such as high-rise buildings, multi-span bridges, dams, pre-stressed concrete, elevated highways, etc.

Moreover, the extract of alkaline solution (lye) produced from WA has not been given attention. Lye produced for other purposes such as soap making, and agricultural purposes possessed similar properties to NaOH. NaOH is an inorganic compound consisting of sodium cations Na<sup>+</sup> and hydroxide anions OH<sup>-</sup> [76]. It is a highly alkaline solution with a pH value of 14 that may cause severe chemical burns. Similarly, lye is produced through the leaching process of WA, also is a robust alkaline solution that has been used over decades in agricultural and other sectors. WA lye, like NaOH, is caustic and has a pH value above 13. Therefore, relevant studies needed to be conducted to assess the possibility of using WA lye as an alkaline activator in geopolymer concrete production.

## CONCLUSIONS

The findings from various studies on WA application in concrete has revealed its effective utilisation as either cement replacing material in mortar/concrete or as a binder in geopolymer concrete. Although the percentage replacement is at a lower level, its usage in mortar/concrete

production will help address the sustainability problems related to WA waste disposal. The findings can be summarised as follows. Some parameters, including combustion temperature, furnace type and hydrodynamics, and mother tree species, were discovered to affect the quantity and quality of WA.

WA possessed a significant amount of  $K_2O$ , making it a good alkaline activator in geopolymer mortar/concrete. WA has a large specific surface area because its particle form is very irregular and generally porous. The increased of WA content as a substitution of cement in mortar/concrete production resulted in a high water demand of the mortar/concrete. This shows that WA is hygroscopic in nature. Addition of WA in normal mortar/concrete delayed both the initial and final setting time which was linked to the high surface area, LOI and hygroscopic property of the WA. The study revealed that the utilization of WA as SCM at up to 20% replacement can improve the long term strength and durability properties of mortar/concrete due to the long term pozzolanic effect of the WA that contribute towards formation of more compact internal structure. Further increase in the WA dosage shows a negative effect on the mortar/concrete properties. When WA is included at up to 50% replacement of binder in geopolymer matrix, the highly alkaline mineral from the WA plays a role of alkaline activator activating the aluminosilicate compounds in the matrix. Subsequent increment in the WA content led to reduction in the aluminosilicate compounds and hence adversely affect the geopolymerization process. The inclusion of WA in geopolymer mortar/concrete increase the water demand of the mixture and hence affect its workability. A super plasticizer may be required to obtain a desired workability. Geopolymer concrete with WA showed a comparatively quick loss of workability. The considerably high viscosity and surface adhesion features of the fresh geopolymer concrete with WA made vibrating the concrete more challenging compared to conventional fresh concrete. In order to facilitate geopolymer concrete vibration in field application, additional water needs to be added in the mixture. The utilization of WA in normal and geopolymer concrete will promote a cleaner environment by reducing cement consumption and providing means of utilizing the WA waste which may otherwise be landfilled.

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