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The incorporation of wood waste ash as a partial cement replacement material for making structural grade concrete: An overview

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Abstract With increasing industrialization, the industrial byproducts (wastes) are being accumulated to a large extent, leading to environmental and economic concerns related to their disposal (land filling). Wood ash is the residue produced from the incineration of wood and its products (chips, saw dust, bark) for power generation or other uses. Cement is an energy extensive industrial commodity and leads to the emission of a vast amount of greenhouse gases, forcing researchers to look for an alternative, such as a sustainable building practice. This paper presents an overview of the work and studies done on the incorporation of wood ash as partial replacement of cement in concrete from the year 1991 to 2012. The aspects of wood ash such as its physical, chemical, mineralogical and elemental characteristics as well as the influence of wood ash on properties such as workability, water absorption, compressive strength, flexural rigidity test, split tensile test, bulk density, chloride permeability, freeze thaw and acid resistance of concrete have been discussed in detail.

1. Introduction

In the current years, the concern of our global environment and increasing energy insecurity has led to an increasing demand in renewable energy and their sources. Among these resources, biomass resources (forestry and agricultural wastes) and power plants fueled by them are a promising source of renewable energy with an economically low operational cost and continuously regeneration of the fuel. Also it is considered a CO_2 neutral energy resource as consumption rate is lower than growth rate. Additionally, the use of forest and timber industry by products such as sawdust, woodchips, wood bark, saw mill scraps and hard chips in the production of power

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presents an efficient method for the disposal of the aforementioned industrial by products. The thermal incineration significantly reduces the mass and the volume of the waste thus providing environmentally and economically safe solid waste management [1]. It is a common practice in the timber product manufacturing industry to draw power for the industrial processes from the wood wastes by developing small scale boilers units and using wood wastes as chief sources of energy. Moreover in the presence of proper emission controls such as electrostatic precipitator, there is virtually little or no emission, thus rendering it an environmentally safe fuel. Wood wastes' fuels are preferred more than other biomasses (herbaceous and agricultural) due to reduced fly ash and other residue production [2].

Among the technologies available for power and heat production, solid biomass combustion is a proven technology in which technologies of fluidized bed and grate furnace combustion are mainly used [3,4]. But a major problem arising from regular use of forestry and timber biomass is the production of ash as a by-product which is a major environment pollutant and health hazard in the absence of emission controls, most of which are also very expensive. Thus, increasing the number of biomass fueled thermal power plant will lead to the generation of vast amount of wood ash which would need proper monitoring and sustainable management of the ash. In the current trend, approximately 70% of wood ash is land filled, 20% tends to be used as a soil supplement in agriculture and 10% are employed as other uses mainly in metal recovery and pollution control [5,6]. The characteristics of ashes from the biomass may differ and chiefly depend on (1) biomass characteristics such as herbaceous or wood or bark (2) combustion technology such as fixed or fluidized beds (3) and the location where collection of ash is done [7]. Combustion of wood produces less ash whereas agricultural wastes and bark have more ash content and thus produce more ash content. Also, the biomass combustion technology controls the properties and amount of ash produced. In a grate furnace, the biomass are subjected to high temperature which volatizes the organic species such (salts and heavy metals), thus reducing their content in the ash [3,7,8,].The difference in operating temperature of the furnace characterizes the degree of fouling and slagging in the ashes. The hydro dynamics of the furnace control the biomass ash fractions collected in the grate furnace and the amount of bottom ash is dominant compared to multi cyclone or filter whereas fly ash is quantitatively larger in case of fluidized bed.

Most of the biomass ash generated in thermal plant is either disposed of in a landfill or recycled in open agricultural fields without any control. But in recent days, land filling is becoming limited due to scarcity of waste land, increasing environmental concerns and the ever increasing volume of ash. Contamination of ground water resources is a major problem due to leaching of heavy metals from the ash or by seepage of rain water in case of land filling. Moreover, the use of wood ash as a soil supplementary material is getting increasingly restrictive due to significantly high metal content in ashes, especially wood ash, which may cause hazards in case of groundwater contamination and infertility of agricultural fertile land. In this regard many researches and studies are being carried out to use wood ash, especially in construction materials to develop a sustainable way of its disposal.

The current boom in the construction industry has caused an exponential increase in the demand of cement, which is the primary constituent in the production of concrete. The production of cement needs a massive amount of raw material and energy, and at the same time releases carbon dioxide into the atmosphere. Researchers have shown that for every 600 kg of cement, approximately 400 kg of CO_2 is released into the atmosphere. The increasing demand of cement leads to higher rate of environmental degradation and more exploitation of natural resources for raw material. The use of wood ash as partial cement replacement in concrete reduces the requirement of hydraulic cement to a large extent [9]. Researchers [10–13] have conducted tests which showed promising results for wood ash being suitably used to replace cement partially, in concrete production. These results solved twofold problems by providing a solution to the waste management problem of wood ash and by minimizing the usage of energy extensive hydraulic cement. Thus incorporating usage of wood ash as replacement for cement in blended cement is beneficial for the environmental and leads to a sustainable and symbiotic relationship.

2. Factors affecting the quantity and quality of wood waste ash

There are several factors which influence the qualitative and quantitative aspects of wood ash produced from its combustion. This facilitates the need of proper characterization of wood ash before employing it to partially replace cement. These factors include combustion temperature, types and hydrodynamics of the furnace and the species of trees from which the wood is derived.

The combustion temperatures of the wood waste influence both the yield and chemical composition of the wood ash. Combustion of the wood waste at higher temperature leads to the production of lower amount of ash. It was observed that wood ash production reduced by 45% when the combustion temperature was raised from 538 °C to 1093 °C. Combustion at higher temperatures, above 1000 °C causes decomposition of carbonates and bicarbonates and thereby decreases the alkalinity of the ash due to their reduction in the ash, being chemical species contributing to the alkalinity of the wood ash. At an incineration temperature of below 500 °C, carbonate and bicarbonate compounds, especially calcite ($CaCO_3$), are predominant in wood ash [2] whereas at higher incineration temperatures like 1000 °C, oxide compounds such as quick lime (CaO) are in majority, in the chemical phase of wood ash. Moreover, the presence of light metallic elements such as potassium, sodium and zinc decreases upon increasing the combustion temperature [13].

Different types of combustion technologies affect the physical properties of ash and varying the thermal temperature causes corresponding variation in the chemical composition of wood ash. Generally, wood ash produced in a grate fired furnace has a tendency to be coarser in nature and settle inside the chamber as bottom ash whereas in more efficient fluidized bed furnaces, the ash produced is finer, with a very low fraction of coarse particles.

The chemical characteristics of wood ash, which govern its credibility to be used as a replacement for cement, such as silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3) and quicklime (CaO) differ significantly from one species of trees to another.

Variation in the chemical characteristics of ash produced from different species of trees is given in Table 1.

(1) To maintain optimum level of soil pH for the desired crop growth. The calcium carbonate equivalent of different wood ash may vary but all lie in the range of 25–60% [15].
(2) It has been used as a partial replacement of lime or cement kiln dust in the solidification of hazardous waste.
(3) It is also employed for odor as well as pH control of hazardous and non-hazardous wastes due to its excellent liming characteristics. It is also advantageous for color and odor control in the compost and in capturing contaminants on its highly porous surface.
(4) Wood waste ash is also used as filler material in the building of flexible pavements, roads and highways [13].
(5) Due to its high carbon content, its use is limited to low and medium strength concrete materials in construction industry but it has high potential in numerous other materials such as controlled low strength material(CLSM), low and medium strength concrete, masonry products, roller compacted concrete pavements (RCCP), material for road base [16].
(6) Recently it was reported that wood ash has excellent potential to be employed as pozzolanic admixture and activator in cement based materials [16].

3. Physical properties of wood ash

Naik studied the physical and chemical characteristics of wood ash sourced from different mills [16]. Wood ash was observed to be a heterogeneous mixture of different sized particles generally angular in shape. These particles basically consisted of partially burned or unburned wood and bark. To evaluate fineness, average amount of wood fly ash passing sieve #200(75 μm) is 50% and percentage of ash retained on sieve #325 (45 μm) is 31%. Test results showed the average unit weight of (ASTM C 29) of fly ash and bottom ash as 490 kg/m^3 and 827 kg/m^3 respectively and average specific gravity was 2.48 and 1.65 respectively. The average water requirement for fly ash was 116% and average auto clave expansion test value 0.2%.

Udoeyo et al. [11] evaluated the physical properties of waste (WWA) wood ash used as partial replacement of cement. He reported that WWA had a specific gravity of 2.43, 1.81% of moisture content and a pH of 10.48. The average loss on ignition was 10.46.

Rajamma et al. [7] reported the specific gravity of wood fly ash to be 2.54 collected from a forestry biomass fired power plant and observed finer particles with average diameter of 50 μm. Wood ash was mainly found to be composed of highly angular particles with extensive surface porosity seen through SEM images.

Naik et al. studied wood ash from five various sources and they were designated as W1–W5 [12]. Specific gravity of different sources wood ash varied between 2.26 and 2.60 and fineness of the wood ash (% retained on 45 μm sieves) was between 23% and 90%. Physical properties of all the wood ashes are given in Table 2.

4. Elemental analysis

Campbell reported that wood ash contains carbon in the range of 5–30%. Calcium (7–33%), potassium (3–4%), magnesium (1–2%), manganese (0.3–1.3%), phosphorus (0.3–1.4%) and sodium (0.2–0.5%) are the major constituents of wood ash. With increasing carbon content, density of wood ash decreases [5]. The chemical and physical characteristics depend on type of wood, combustion temperature etc.

Naik et al. obtained wood from Rothschild, Wisconsin in United States and reported its elemental analysis and compared it with Type-I cement [17]. Instrumental Neutron Activation Analyzer was used for the analysis. It was found that elemental composition of wood ash differed considerably from cement. Wood ash mainly contained Aluminum, Cadmium, Iron, Magnesium, Manganese, Potassium, Sodium and Titanium whereas cement contains Aluminum, Calcium, Iron and Potassium. The wood ash registered much higher amounts of Magnesium, Manganese, Potassium, Aluminum and Sodium than cement.

Mishra et al. in their study, researched upon the elemental and molecular composition of mineral matter in wood ash, from five different wood sources and two types of bark with respect to temperature [18]. When the temperature was increased from 500 to 1300 °C the loss incurred was in the range of 23-48% which was due to the decrease in elemental mass concentration of K, S, B, Na and Cu due to temperature increase.

5. Chemical composition

Etiegni and Campbell and Etiegni reported that major oxides in the wood ash are lime (CaO), portlandite ($Ca(OH)_2$), Calcite ($CaCO_3$) and calcium silicate (Ca_2SiO_4) [6,19]. The possible hydration of lime and silicates present in the wood ash were

Table 1 Chemical composition of wood ash from various species of timber [14].

Biomass group	SiO_2	CaO	K_2O	P_2O_5	Al_2O_3	MgO	Fe_2O_3	SO_3	Na_2O	TiO_2
Bitch bark	4.38	69.06	8.99	4.13	0.55	5.92	2.24	2.75	1.85	0.13
Forest residue	20.65	47.55	10.23	5.05	2.99	7.2	1.42	2.91	1.6	0.4
Pine bark	9.2	56.83	7.78	5.02	7.2	6.19	2.79	2.83	1.97	0.19
Pine chips	68.18	7.89	4.51	1.56	7.04	2.43	5.45	1.19	1.2	0.55
Poplar	3.87	57.33	18.73	0.85	0.68	13.11	1.16	3.77	0.22	0.28
Poplar bark	1.86	77.31	8.93	2.48	0.62	2.36	0.74	0.74	4.84	0.12
Sawdust	26.17	44.11	10.83	2.27	4.53	5.34	1.82	2.05	2.48	0.4
Spruce bark	6.13	72.39	7.22	2.69	0.68	4.97	1.9	1.88	2.02	0.12
Spruce wood	49.3	17.2	9.6	1.9	9.4	1.1	8.3	2.6	0.5	0.1
Wood residue	53.15	11.66	4.85	1.37	12.64	3.06	6.24	1.99	4.47	0.57

Table 2 Physical properties of wood ash [12].

Test	W1	W2	W3	W4	W5
Retained on no. 325 sieve	23	60	90	40	12
Strength activity index with Portland cement					
3 days	88	38	102.0	53.8	112.3
7 days	84	39	83.3	59.3	72.0
28 days	88	34	78.7	59.4	67.0
Water requirement, % of control	115	155	115	126	130
Autoclave expansion, %	0.2	0.5	−0.6	−0.22	0.12
Specific gravity	2.26	2.41	2.60	2.26	2.33

attributed to, for the swelling of wood ash in rainy season by the author.

Naik et al. reported the chemical characteristics of wood ash from five different varieties of wood to study the potential of their use in CLSM [12]. The LOI was found to range from 6.7% to 58.1% and moisture percentage varied between 0.5% and 3.3%. The chemical properties of all the five sources wood ash are tabulated in Table 3.

Udoeyo et al. [11] reported the oxide concentration of the ash using an X-ray diffraction (XRD) test and showed that its major oxide concentration are CaO, SiO_2, Al_2O_3, K_2O, Fe_2O_3, MgO, SO_3, TiO_2 and P_2O_5. Compounds such as Na_2O, ZnO, Cl, MnO, SrO, Cr_2O_3, CuO, ZrO_2 and Rb_2O were detected in trace amount. The chemical analysis confirmed that the ash has Silicon dioxide (SiO_2), Aluminum dioxide (Al_2O_3) and iron oxide (Fe_2O_3) with values 20.8, 11.6 and 5.37 respectively. But combining the percentage masses of these oxides gives a total of 37.8% which is less than 70%, the limit specified for pozzolan in ASTM C 618 (1994).

Rajamma et al. [7] analyzed the wood waste ash from Electrostatic precipitator from fuel plant using X-ray diffractometry. Results of XRD tests showed the presence of silica and calcite. LOI of fly ash samples was determined to be 14% and 7% respectively. It also confirmed the presence of SiO_2, Al_2O_3 and Fe_2O_3 in the wood ash, which controls the pozzolanic reactivity. Table 4 shows the chemical composition of wood waste ash as given by various researchers.

6. Mineralogical analysis

Campbell tabulated the major and trace compounds and elements in the wood ash. Carbon content was found to range between 4% and 34% in the wood ash [5]. The major elements were calcium (7–34%), potassium (3–4%), magnesium (1–2%), phosphorus (0.3–1.4%), manganese (0.3–1.3%) and sodium (0.2–0.5%) and the trace elements were zinc, boron, copper, molybdenum at per million levels.

Naik et al. reported that quartz (SiO_2) is the dominant phase in the wood waste ash [17]. Gypsum ($CaSO_4{\cdot}H_2O$), magnetite (Fe_3O_4), microcline ($KAlSi_3O_8$), mullite ($Al_2O_3{\cdot}SiO_{20}$), periclase (MgO) and plagioclase (NaCa) were also detected in trace amounts. 46.9% of amorphous materials were also detected in the wood ash. The calcite, hematite, magnetite, microcline, mullite, plagioclase and quartz were non-reactive in concrete.

Table 3 Chemical composition of wood ash used [12].

Analysis parameter	W1	W2	W3	W4	W5
Silicon dioxide (SiO_2) (%)	32.4	13.0	50.7	30.0	8.1
Aluminum oxide Al_2O_3 (%)	17.1	7.8	8.2	12.3	7.5
Iron oxide, Fe_2O_3 (%)	9.8	2.6	2.1	14.2	3.0
Calcium oxide, CaO (%)	3.5	13.7	19.6	2.2	25.3
Magnesium oxide, MgO (%)	0.7	2.6	6.5	0.7	4.5
Potassium oxide, K_2O (%)	1.1	0.4	2.8	2.0	2.7
Sodium oxide, Na_2O (%)	0.9	0.6	2.1	0.5	3.3
LOI (1000 °C)	31.6	58.1	6.7	35.3	32.8
Moisture (%)	2.4	0.5	0.2	0.4	3.3
Available alkali, Na_2O (%)	0.9	0.4	0.8	1.1	4.2

7. Characteristics of concrete with wood ash

7.1. Slump

Udoeyo et al. [11] studied concrete containing varying percentages (5%, 10%, 15%, 20%, 25% and 30%) of waste wood ash as an additive. It was observed that the concrete mix containing WWA showed less workability than that of control specimen for the same water to cement ratio. And it increased with increasing replacement percentage. At 20%, 25% and 30% replacement, it was insensitive to slump. This might have been due to the high organic content of the ash. Table 5 contains the test results for the slump.

Elinwa and Mahmood [9] observed that replacement of cement by wood ash obtained from open burning of sawdust in the manufacturing of grade 20 concrete had an adverse effect on the workability of freshly produced concrete. For the constant water to binder ratio of 0.565, increasing replacement percentage from 5% to 30% of the total binder weight decreased the slump value of the concrete by 5–40 mm with respect to the control mix.

Same result was observed by Udoeyo and Dashibil [10] who attempted to produce grade 25 concrete with a similar replacement percentage (5–30%). Also reduction in compacting factor of concrete mix was observed with increasing level wood ash replacement.

7.2. Water absorption capacity

Udoeyo et al. [11] studied the water absorption of the concrete mixes containing varying replacement percentage of waste wood ash (5–30% by the weight of cement) as additive (Fig. 1). It was observed that with increasing percentage of wood ash replacement, water absorption also increased. The water absorption at 5% WWA content was 0.4% which

Table 4 Summary of chemical composition of wood waste ash.

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	TiO_2	K_2O	Na_2O	SO_3	C	P_2O_5	LOI (%)
[9]	67.20	4.09	2.26	9.98	5.80	–	–	0.08	0.45	–	0.48	4.67
[10]	78.92	0.89	0.85	0.58	0.96	–	–	0.43	–	17.93	–	8.40
[19]	67.20	4.09	2.26	9.98	5.80	–	–	0.08	0.45	–	0.48	4.67
[21]	31.80	28.00	2.34	10.53	9.32	–	10.38	6.50	–	–	–	27.00

Table 5 Slump of concrete with WWA as an additive [11].

WWA content (%)	0	5	10	15	20	25	30
Slump (mm)	62	8	5	2.5	0	0	0

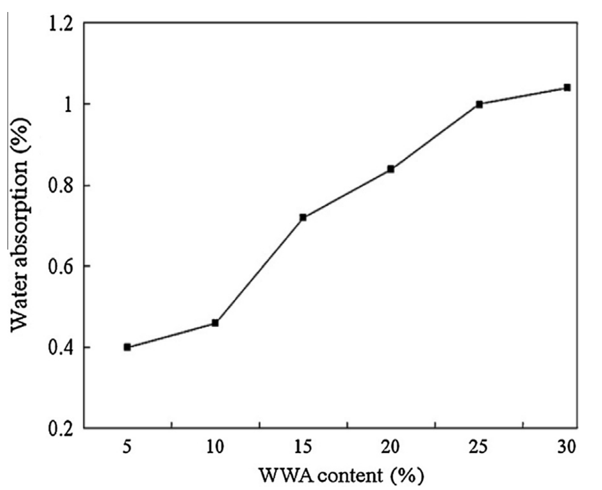

Figure 1 Percentage of water absorption versus ash content of WWA concrete [11].

increased to 1.05% at 30% WWA content. However, these values are far less than the maximum accepted value of 10% for most construction materials.

Elinwa and Ejeh [20] recorded that inclusion of wood waste at 15% percentage replacement material in the mortar reduced the water absorption as compared to the mortar mix with no wood ash. They were studying the effects of replacing cement with waste wood ash in mortar mixes based on the water absorption property. Average water absorption of the mix containing 15% replacement of wood ash and mortar mix, containing no wood ash, was 0.8% and 1.25% respectively, still far below the accepted 10% in most construction materials.

7.3. Soundness

Partially replacing the cement with wood ash in blended cement paste generally causes higher degree of cement paste soundness. Varying the percentage of replacement from 5% to 30%, it was observed that with increasing replacement percentage, soundness of cement paste was also increased. With replacement percentage of 30%, the most sound blended cement paste was 1.45 mm which is still less than the maximum allowable soundness of 10 mm specified by BS 4550-Part 3 [9,10,20].

7.4. Bulk density

Ellinwa et al. observed that when cement was partially replaced by wood waste ash in concrete mixes, there was a reduction in bulk density which becomes more significant at higher replacement percentages [21]. The bulk density of grade 20 concrete mix was reduced to 2281 kg/m^3 at 40% replacement from 2482 kg/m^3 at 0% wood ash. This was attributed to the fact that wood waste ash has a lower specific gravity compared to OPC.

7.5. Compressive strength

Naik et al. studied the compressive strength of concrete mix containing wood ash up to the age of 365 days [17]. The replacement percentage was 5%, 8% and 12% of the total binder weight. Compressive test results are shown in Fig. 2. The conclusions drawn based on the results are

(1) The compressive strength of control mixture was 34 MPa at 28 days and 44 MPa at 365 days;
(2) the strength of concrete mixture with wood ash ranged from 33 MPa at 28 days and between 42 and 46 MPa at 365 days and;
(3) that incorporation of wood ash increased strength development of the concrete mix although cement content was reduced by 15%. This was attributed to the increased pozzolanic activity.

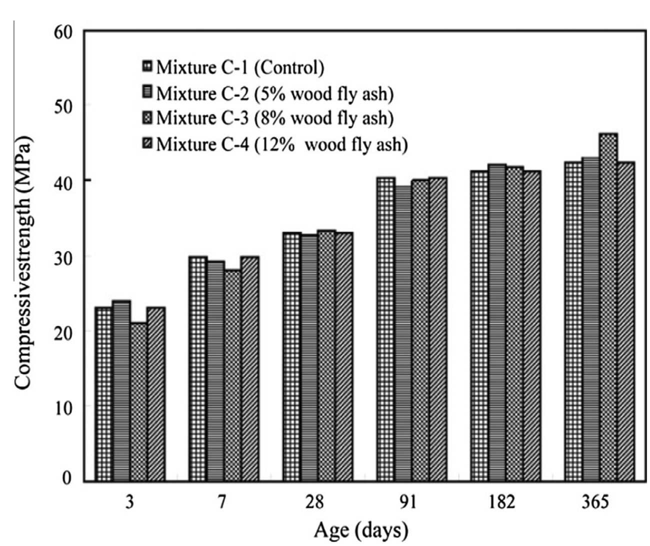

Figure 2 Compressive strength of concrete mix incorporating wood fly ash [17].

Rajamma et al. [7] studied the effects of wood waste fly ash obtained from a wood biomass fired power plant on the compressive strength of cement mortar mixes. Wood waste was used to partially replace cement with replacement percentage being 10%, 20% and 30% of the total binder weight. It was observed that mortar mixes with replacement percentage of 10% of wood ash exhibited higher 28 day strength as compared to the control mixture. But at higher replacement percentage of 20% and 30% of the total binder weight, it was observed that the 28 days strength was reduced, relative to the control mixture of the neat cement mortar mix.

Udoeyo et al. [11] reported the compressive strength of concrete with different replacement percentage (5, 10, 15, 20, 25, and 30 by weight of cement). The results are given in Table 6. There was significant enhancement in strength due to longer curing because silica provided by the wood got adequate time to react with calcium hydroxide produced by hydration of cement.

Ellinwa et al. studied the methodology to increase the compressive strength of wood waste ash/cement concrete mix by the incorporation of trace amount of metakaolin as an additive in the mix with targeted strength of 20 MPa [21,22]. The replacement percentage varied between 0% and 40% with a 5% increment at every step. And metakaolin was added at a constant dosage of 3% by total binder weight. It was observed that addition of metakaolin at small dosages increase the early strength of blended cement concrete. SDA/cement concrete mix with 10% replacement of wood waste ash showed a 37% and 7% increase in the compressive strength and modulus of rupture respectively as compared to the control mixture and all specimens were able to attain the targeted strength after 28 days of curing.

7.6. Split tensile strength

Naik et al. studied the effects of incorporating wood ash on the splitting tensile strength with the replacement percentage of the waste wood ash being 5%, 8% and 12% of the total binder [17]. It was observed that,

(1) The strength achieved by the control mixture was 3.8 MPa at 28 days and 4.3 MPa at 365 days.
(2) The strength of concrete incorporating wood ash ranged between 3.6 and 4.0 MPa at 28 days and between 4.2 and 5.1 MPa at 365 days.
(3) Generally, split tensile strength follows the same pattern as for the compressive strength.

Udeyo and Dashibil [10] studied the spilt tensile strength at 7 days and 28 days of concrete mixes containing saw dust ash as partial replacement of cement. He reported a decrease in split tensile strength with increasing percentage of saw dust ash although it was less pronounced as compared to compressive strength. It was seen that that the difference of the blended cement concrete and control mixture strength became more significant in 7 days and at 28 days blended cement concrete mixes with replacement percentage up to 25% showed the split tensile strength value up to 90% of the strength of control mixes. The results of split tensile strength were given in Table 7 and Fig. 3 depicts the split tensile ratio (spilt tensile strength of blended concrete to normal cement concrete) and ash content in graphical format.

7.7. Flexural strength

Naik et al. investigated the effect of wood ash on the flexural strength [17]. Three replacement percentages (5%, 8% and 12%) of wood ash of the total weight of binder was considered.

The results of flexural strength are shown in Fig. 4. It was concluded on the basis of results that

(1) The control mixture achieved strength of 401 MPa at 28 days and 4.4 MPa at 365 days.
(2) The strength of concrete mixtures incorporating wood ash differed from 3.9 to 4.4 MPa at 28 days and between 4.3 and 5.3 MPa at 365 days.
(3) Test results verified the fact that inclusion of wood ash improved the flexural strength due to pozzolanic reaction of wood fly ash.

Rajamma et al. [7] studied the 28 days flexural strength of mortar cement mixes manufactured by partial replacement of the binder using wood fly ash from two different wood biomass power plant and mortar bars were constructed for flexural testing with replacement percentage of 0% (control mix), 10%, 20% and 30% by total binder weight. Results showed a gradual decrease in flexural strength with increasing percentage of replacement from 0% to 30%. Mortar mix with replacement percentage of 10%, 20% and 30% of wood ash exhibited flexural strength in range of 60.6–71%, 59.6–61.7% and 45–48.6% of the control mix respectively. And it was concluded that

(1) The optimum level of replacement in mortar mix maintaining acceptable mechanical strength is 20%.
(2) At higher replacement percentage above 20%, mechanical strength degraded rapidly.

7.8. Drying shrinkage

Nail et al. [17] studied the drying shrinkage of blended cement concrete mixtures manufactured with wood ash. Replacement percentage was 5%, 8%, and 12% by the weight of the binder (cement). They observed that:

(1) The shrinkage of control mix was −0.0092% at 7 days and −0.052% at 232 days.
(2) Shrinkage of concrete incorporating 5% wood ash was 0.012% at 7 days and −0.027% at 232 days;
(3) For mixture with 8% wood ash shrinkage was 0.014% at 7 days and −0.013% at 232 days and
(4) Mixes incorporating 12% wood ash showed shrinkage between −0.0051% at 7 days and −0.044% at 232 days.

7.9. Resistance against acid attack

Udoeyo and Dashibil [10] studied the resistance of blended concrete mix containing wood waste ash against acid attack. Two sets of concrete specimen with mix proportions 1:2:4 and with water to cement ratio 0.65 were manufactured with one containing neat cement as a binder and other containing

Table 6 Compressive strength of concrete with wood ash as replacement [11].

WWA content (%)	3 day strength (MPa)	7 days strength (MPa)	14 days strength (MPa)	28 days strength (Mpa)	90 days strength (Mpa)
0	16.24 ± 0.10[a]	16.85 ± 0.05	23.40 ± 0.46	28.35 ± 2.64	31.48 ± 0.50[b]
5	14.23 ± 1.04	15.31 ± 0.87	18.32 ± 0.67	24.61 ± 0.51	28.66 ± 0.70[d]
10	14.01 ± 0.86	15.31 ± 0.37	16.92 ± 0.75	21.86 ± 1.11	27.54 ± 0.34[d]
15	13.75 ± 0.62	14.18 ± 0.26	15.78 ± 0.68	21.73 ± 0.84	23.70 ± 0.81[c]
20	13.25 ± 0.47	14.10 ± 0.39	15.78 ± 0.68	20.55 ± 0.79	22.68 ± 0.81[c]
25	13.17 ± 0.36	14.05 ± 0.58	15.03 ± 0.88	20.35 ± 1.16	19.62 ± 0.56[b]
30	12.83 ± 0.30	13.88 ± 0.76	14.85 ± 0.25	19.52 ± 0.57	19.52 ± 0.57[b]

[a] Standard deviations.
[b] Not significant.
[c] $p < 0.05$.
[d] $p < 0.05$.

Table 7 Split tensile strength of saw dust ash concrete [10].

SDA (%)	Split tensile strength at 7 days (N/mm^2)	Split tensile strength at 28 days (N/mm^2)
0	2.14	2.8
10	2.05	2.76
15	1.83	2.69
20	1.79	2.61
25	1.44	2.53
30	1.14	1.91

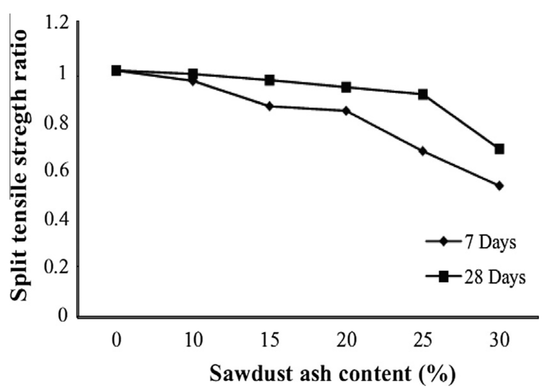

Figure 3 Split tensile strength ratio versus saw dust ash content [10].

15% replacement of wood ash as partial replacement of the binder. The hardened specimen cubes were immersed in 20% concentration nitric acid solution and loss of mass was noted at 7, 14, 212, 28, 35, 42, 49, 56, 63 and 70 days. Both sets registered a marginal increase in mass up to 9 week due to absorption of water. At tenth week absorption decrease in mass was registered for both the specimens but the loss of mass in control mixture was more pronounced as compared to blended cement concrete.

7.10. Chloride permeability

Horsakulthai et al. [23] investigated the possibility of using very finely ground ash from the combined combustion of wood, rice husk and sugar cane bagasse waste (BRWA) as

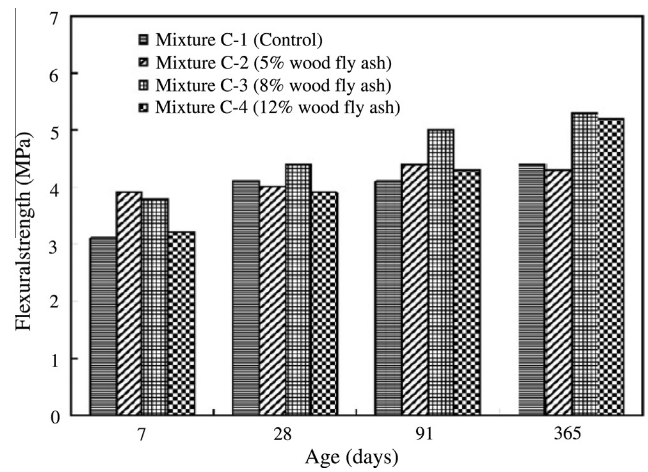

Figure 4 Flexural strength of concrete mixtures incorporating wood fly ash [17].

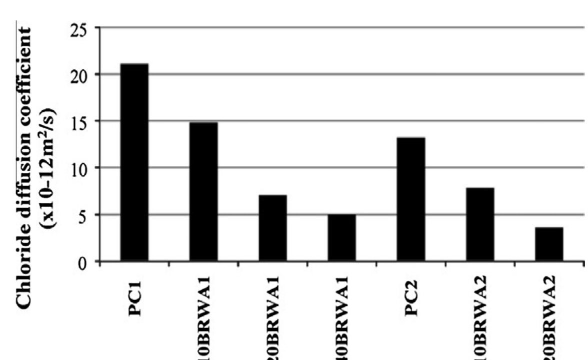

Figure 5 Chloride diffusion coefficient of concrete at age of 28 days [23].

partial replacement of cement on the chloride permeability of the concrete mix. Accelerated salt ponding was employed for two different grade concrete mixes (grade 20 and 35) with replacement percentage of 0%, 10%, 20% and 40% of total binder mass to test the chloride permeability. It was found that incorporation of BRWA enhanced the chloride permeability and decreased the chloride diffusivity coefficient. At 10%, 20% and 40% replacement percentage the chloride diffusion coefficient reduced by 30–40%, 65–70% and 75% respectively as compared to control mixture. Fig. 5 depicts the trend of chloride diffusion coefficient with different replacement percentage of BRWA.

7.11. Freezing and thawing resistance

Naik et al. investigated the effects of wood ash on the freezing and thawing resistance of concrete [17]. Test was done by evaluating the changes in relative dynamic modulus, pulse velocity and change in length. The replacement percentage was taken to be 5%, 8% and 12% of total binder weight. There was no important effect of the freeze-thaw cycle (300 cycles) on the relative dynamic modulus on the concrete mixes and thus it was concluded that incorporation of wood ash did not produce significant difference in relative dynamic modulus. For control mixture, relative dynamic modulus was 97.7% and it was 95.7% for 5% replacement percentage of wood ash, 97.8 for 8% and 95.7% for 12% replacement of wood ash by weight of binder. Also, no significant effect was observed on pulse velocity with the incorporation of wood ash. For control mixture the pulse velocity was 5425 m/s, for 5% it was 5480 m/s, for 8% it was 5560 m/s and for 12% replacement by weight of cement, the pulse velocity was 5435 m/s.

8. Practical application

Eliche-Quesada et al. [24] produced lightweight bricks by blending clay with variety of waste materials such as sawdust, spent earth from oil filtration, compost and marble. Brick samples were casted respectively with 0–10% sawdust, 0–30% spent earth from oil filtration, 0–30% compost and 0–20% marble. At a constant pressure of 54.5 MPa, bricks were molded and fired in a laboratory furnace at a rate of 3 °C/min upto respectively 950 and 1050 °C for 4 h. It was found that bricks fired at 1050 °C had a higher compressive strength, lower water absorption and porosity as compared to bricks molded at 950 °C. At 5% sawdust, 15% spent earth from oil filtration, 10% compost or 15% marble was deduced to be the optimum amount of waste material. But successful commercial utilization of Wood Ash in construction industry is limited as the study of wood ash and its use is in research stage. Also, wood ash may contain contaminants within them yet unknown to the current research, which may need effective and safe immobilization. Relevant standards should also be developed which will promote the production and application of construction entities developed from wood ash. Standardization plays a prominent role in spreading knowledge, implementing research results and decreases time to markets for innovations [25].

9. Results and conclusion

(1) Quantity and quality of wood ash may vary with many factors such as combustion temperature, species of wood and combustion technology used. Hence proper analysis of wood ash is important before its application in concrete.
(2) Wood ash chemical characteristics differ with species of wood but chiefly contains lime and silica.
(3) The particles of wood ash are coarser than that of cement and have higher specific surface as compared to cement due to porous nature and irregular shape.
(4) Incorporation of wood ash as partial replacement of cement adversely decreases the slump of concrete.
(5) There was an increase in water absorption with increase in wood ash percentage.
(6) There was marginal decrease in strength with increasing wood ash percentage in concrete, but increased with age due to increased pozzolanic reactions. Split tensile strength also followed the same trend.
(7) Bulk density was gradually reduced with increasing percentage of wood ash.
(8) Wood ash at replacement percentage up to 10% of the weight of binder can be successfully used as additive in place of cement to produce structure grade concrete.
(9) Replacement of cement by wood ash does not have negative impact on the chloride permeability.
(10) The incorporation of wood ash in concrete does not have negative impact on its ability to resist freeze thaw resistance.
(11) There was a significant decrease in the drying shrinkage on the incorporation of wood ash.
(12) Water absorption increased with increasing wood ash percentage.

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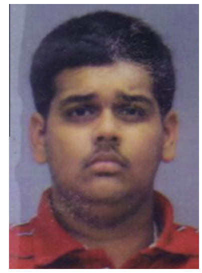

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