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INTRODUCTION

Wood ash is generated as a by-product of combustion from boilers at pulp and paper mills, steam power plants, and other thermal power generating facilities. Since wood is a renewable resource for energy and an environmentally friendly material, there is an increased interest in using “waste” wood for energy production. As a result, there will be increased amount of wood ash generation. Currently, most of the wood ash generated in the USA is either landfilled (about 70%) or applied on land as a soil supplement (about 25%). The cost of landfilling is increasing due to strict environmental regulations and limited availability of landfill space. Presence of some heavy metals and/or high-alkalinity in wood ash may limit its application on land under a stricter environmental regulation. In light of these, it is essential to develop beneficial uses of wood ash to solve the concerns associated with its disposal. Wood ash consists of two different types of materials: fly ash and bottom ash. Knowledge of the various properties of wood ash such as physical, chemical, and microstructural properties is necessary to establish beneficial applications for them. These properties depend upon several factors including type and source of wood, design and operating parameters of the boiler (especially combustion temperature), and ash collection methods. This

investigation was undertaken with a view to understand various physical, chemical, and, microstructural properties of wood ash derived from various sources in the USA and Canada; and, to determine its potential applications in cement-based construction materials.

PHYSICAL PROPERTIES

Currently, ASTM specifications do not exist for wood ash for determining their suitability for use as construction materials. Therefore, ASTM C 618, developed for volcanic ash and coal fly ash for use in concrete, was used to determine general suitability of wood ash for potential application as a mineral admixture in cement-based materials. The following physical properties for each source of wood ash were determined: moisture content, particle size distribution, unit weight, cement pozzolanic activity, water requirement, and autoclave expansion. Properties of twelve sources of wood fly ash and five sources of wood bottom ash are reported in this paper.

As-received moisture content of wood fly ash and bottom ash was determined in accordance with ASTM C 311. The average moisture content values were about 15% (ranged from 0.9% to 42.3%) for fly ash and 22% (ranged from 0.2% to 68.8%) for bottom ash. Moisture content of wood fly ash should be maintained very low to minimize any possible cementitious and/or pozzolanic reactions that may occur in presence of moisture and/or lime. Additionally, shipping costs to the potential user will be reduced if moisture content is kept at a low level. In order to produce good quality cement-based products incorporating wood ash, not only moisture content of wood ash should be kept low but also variability in moisture content should be minimized.

All wood ashes tested were first oven-dried at $210\text{ }^{\circ}\text{F} \pm 10\text{ }^{\circ}\text{F}$ and then tested for gradation in accordance with ASTM C 136 using standard sieve sizes (one inch through #100). Gradation of wood ashes tested is reported in Table 1. The average amount of wood fly ash and bottom ash passing sieve #200 (75 μm) after washing (ASTM C 117) was 59.9 % (ranged from 10.5% to 98.8%) and 8% (ranged from 1.2% to 18.5%), respectively. The average amount of wood fly ash retained on No. 325 sieve (ASTM C 430) was 46%, which varied between 3.6 and 98.3 percent. Typical particle size distribution (combined ASTM C 136 and ASTM C 422) for wood fly ash is shown in Fig. 1.

The above test results indicate that wood bottom ash may be acceptable as a substitute for sand replacement in ready-mixed concrete and/or as both coarse and fine aggregate replacements in dry-cast concrete products such as bricks, blocks, and paving stones because of its coarse gradation. Wood fly ash can be used as a partial replacement of cement and fine aggregates in the manufacture of concrete and other cement-based products.

Test results for unit weight or bulk density (ASTM C 29) for wood fly ash exhibited average density value of 548 kg/m^3 (34.2 lb/ft^3). It ranged from 162 to 1376 kg/m^3 (10.1 lb/ft^3 to 85.6 lb/ft^3). For wood bottom ash the average was 827 kg/m^3 (51.6 lb/ft^3). It ranged from 663 to 977 kg/m^3 (41.4 lb/ft^3 to 61 lb/ft^3). These results indicate that the wood fly ash and bottom ash may be suitable for replacing light-weight sand and coarse aggregates in making lightweight Controlled Low Strength Materials (CLSM), cast-concrete products such as bricks, blocks, and paving stones, and other cement-based materials.

Specific gravity tests (ASTM C 188) showed an average specific gravity value of 2.45 (varied between 2.32 to 2.76) for wood fly ash, which is similar to a typical coal fly ash. Specific gravity tests (ASTM C 128) for wood bottom ash showed an average specific gravity value of 1.70 (varied between 1.65 to 1.75). This is considerably lower than that for typical natural sand and coarse aggregates used in concrete, which is approximately 2.65.

The average saturated surface dry (SSD) moisture content (ASTM C 128) values were 11.8% (varied between 10% to 14.7%) for wood fly ash and 7.5% (varied between 7.3% to 7.7%) for wood bottom ash. These values are substantially higher than a typical natural or crushed sand or coarse aggregates used in concrete, which is typically less than 2%, but similar to coarse bottom ash from coal-burning plants. Such higher absorption value materials may lead to better curing of the cement-based materials, especially those made at low-water to cementitious materials ratio; and, therefore, it leads to better quality for such materials.

Cement activity index tests were performed in accordance with ASTM C 311/C 109. The average activity index at the age of 28 days for wood fly ash was 73% of the Control (varied between 48.9% to 123.8%) which was lower compared to the ASTM C 618 requirement for coal fly ashes (minimum 75%). The average wood fly ash cement activity index shows that wood ash may be suitable for making medium strength (up to 6,000 psi compressive strength) concrete.

The water requirement (ASTM C 311) for wood fly ash exhibited an average value of 118% (varied between 103% to 155%), which was higher than the maximum desirable value for the water requirement for coal fly ash per ASTM C 618. However, the wood fly ashes may perform

satisfactorily in cement-based construction materials, even though the water required for a desired amount of workability might be slightly higher.

Autoclave expansion tests (ASTM C 151) for wood fly ash exhibited a lower average expansion value of 0.10% (varied between 0.01% to 0.63%), which is below the acceptable maximum limit of expansion/contraction of 0.8% specified by ASTM C 618 for coal fly ash. Therefore, all wood fly ashes are acceptable in terms of long-term soundness/durability from the viewpoint of undesirable autoclave expansion.

CHEMICAL PROPERTIES

Wood ash samples were analyzed for total chemical make-up by the Instrumental Neutron Activation Analysis (INAA). Knowledge of total elemental concentration is necessary because it provides an insight into the potential leaching characteristics of the material tested. The test results for wood ash showed several elements having concentrations in excess of 0.1% (1000 ppm) including aluminum, cadmium, chlorine, iron, magnesium, manganese, potassium, selenium, sodium, titanium, and zinc.

X-ray fluorescence was used to determine chemical composition of wood ash in terms of silicon oxide (SiO_2), aluminum oxide (Al_2O_3), iron oxide (Fe_2O_3), calcium oxide (CaO), magnesium oxide (MgO), titanium oxide (TiO_2), potassium oxide (K_2O), and sodium oxide (Na_2O). The results are shown in Table 2. Loss on ignition (LOI), moisture content, and available alkali (Na_2O equivalent) for the pre-dried fly ashes were also determined and are listed in Table 2. The calcium

oxide contents of the wood ashes were generally above the values for a typical ASTM Class F fly ash with an average of 16% for wood fly ash and 11.4 % for wood bottom ash (Table 2). Furthermore, the magnesium oxide values (average as well as range of values) for wood fly ash and bottom ash were lower than the maximum value of MgO found in typical coal fly ash. Therefore, these wood ashes tested should not have soundness/durability-related problems created due to a high MgO value. The average value of SO₃ present in the wood fly ashes was 4.8% (varied between 0.1% to 15.3%). The average value is less than the maximum 5% permitted by ASTM C 618 for coal fly ash. In general, all oxides present in wood ashes, except SO₃ and the available alkali (Na₂O equivalent), were within limits specified in the ASTM C 618 requirement as shown in Table 2.

The average value of available alkali in wood fly ash was 3.3%, which is significantly above maximum allowable alkali (1.5%) for coal fly ash in accordance with ASTM C 618. The presence of a high amount of alkali may lead to a favorable acceleration of early-age hydration reactions in coal fly ash, natural pozzolans, ground granulated blast-furnace slag, silica fume, and/or metakaoline types of reactive-powder additives used in making cement-based construction materials. However, available alkali may also impact cement-based construction materials negatively due to the possible alkali-silica reaction (ASR) in presence of reactive aggregates and/or high-alkali portland cement.

The average loss on ignition (LOI) value was about 23.4 % (varied between 6.7% to 58.1%) for wood fly ash and 9.9 % (varied between 1.4% to 33.2%) for wood bottom ash. These LOI values are noticeably higher than 6% maximum permitted by ASTM C 618 for coal fly ash.

However, under certain circumstances, ASTM C 618 permits up to 12% maximum LOI. Recent research at the UWM Center for By-Products Utilization and elsewhere have shown that high-LOI (up to 50%) coal fly ash can be used in manufacture of CLSM and/or medium-strength non-air entrained concrete.

The mineral analysis for wood ashes was conducted by using XRD. The results revealed presence of both amorphous (non-crystalline) and non-amorphous (crystalline) phases in wood fly ash. The results showed average amorphous material (glassy constituents) of about 72% (varied from 46.6% to 94.2%) for fly ash and 66% (varied between 53.8% and 73.3%) for bottom ash, which were lower compared to the value for a typical coal fly ash (around 80%). The remaining minerals in crystalline form were nearly the same in both wood fly ash (33%) and bottom ash (34%).

Since the glassy (amorphous) components of wood ash participate in pozzolanic reactions, a higher amount of glassy phase is preferred when a wood ash is used as a replacement of portland cement. Several crystalline phases such as Quartz (SiO_2), Calcite (CaCO_3), Lime (CaO), Portlandite ($\text{Ca}(\text{OH})_2$), Tricalcium Aluminate ($\text{Ca}_3\text{Al}_2\text{O}_6$), Magnetite (Fe_3O_4), Anhydrite (CaSO_4), Mullite ($\text{Al}_2\text{O}_3\cdot\text{SiO}_2$), and Merwinite ($\text{Ca}_3\text{Mg}(\text{SiO}_4)_2$), were present in varying amount in the wood ashes tested.

SCANNING ELECTRON MICROSCOPY (SEM)

SEM pictures of wood ashes were obtained to understand the microstructure of wood ash

particles. Typical micrographs of wood fly ash and bottom ash are shown in Fig. 2. The SEM micrographs show wood ashes as heterogeneous mixture of particles of varying sizes. They are generally angular in shape. Partially hydrated, unhydrated, and hydrated compounds of calcium are also present. Some of the wood ash fly ash particles are porous (cellular form) and/or agglomerated particles. These cellular particles are mostly unburned or partially burned wood chips, knots, or bark particles.

CONSTRUCTIVE USE OPTIONS FOR WOOD ASH

The analysis data presented revealed that wood fly ash generally does not strictly conform to ASTM C 618 requirements for applications in cement-based materials. However, based on physical, chemical, and microstructural properties of wood ash, it is apparent that potential exists for several applications in cement-based materials including CLSM, low- and medium-strength concrete, cast-concrete products, roller-compacted concrete pavements (RCCP), road base course materials, and blended cements. However, for commercial applications of wood ash in these materials, further testing and evaluation of each product made with wood ash is continuing.

Recently completed projects show that structural concrete containing wood ash can be made with 28-day to 91-day compressive strength of 41 to 52 MPa (6,000 to 7,500 psi). Mixture proportions and properties (compressive strength and splitting tensile strength) of concrete containing 25% of wood ash, and 25% and 35% of wood ash and coal fly ash are given in Table 3 and Table 4, respectively. Currently on-going and recently completed activities show that air-entrained concrete applications are also possible. Furthermore, a log-yard sorting area and a

parking lot concrete construction are planned for the summer of 2002 using wood ash as a new source of pozzolanic material. Some data for a planned application of wood ash in manufacture of CLSM is presented in Fig. 3. Use of CLSM will also be a part of the summer 2002 demonstration project. CLSM can have compressive strength between 0.1 and 8.3 MPa (10 and 1200 psi) at the age of 28 days, according to ACI Committee 229. CLSM is used for foundation, bridge abutment, retaining wall, utility trench, as backfill; and as embankment, grouts, abandoned tunnel and mine filling for stabilization of such cavities.

Mixture proportion of CLSM mixtures reported in Fig. 3 consisted of a typical wood fly ash, 635 to 775 kg/m³ (1070 to 1310 lb/yd³); cement, 4 to 195 kg/m³ (6 lb/yd³ to 330 lb/yd³); and water, 580 to 1105 kg/m³ (980 lb/yd³ to 1865 lb/yd³). They were proportioned to obtain a maximum compressive strength of 0.7 MPa (100 psi) at the age of 28 days. This limit on compressive strength was specified to allow future excavation if needed. The compressive strength data as a function of age are plotted in Fig. 3. The compressive strength values were up to 0.8 MPa (120 psi) at 7 days, 1.6 MPa (230 psi) at 28 days, 1.8 MPa (265 psi) at 91 days, and 2.5 MPa (320 psi) at 182 days (Fig. 3). Mixtures P11 through P15, and P20 exhibited compressive strengths in the range of 0.1-0.5 MPa (12 - 74 psi) at the age of 28 days. These mixtures are generally suitable for application such as excavatable CLSM. Since Mixture P16 showed compressive strength below 0.1 MPa (10 psi) at all ages, it was rejected for use as CLSM. Mixture P21 attained compressive strength exceeding 0.7 MPa (100 psi) at the age of 28 days. Therefore, this mixture can be used as a permanent fill material. The results also indicated that excavatable CLSM could be manufactured for commercial applications with large amounts of wood fly ash and low amount of cement at a high water-to-cementitious materials ratio.

CONCLUSIONS

The following general conclusions are drawn, based on data collected in this project.

- The effects of source of wood ashes on physical, chemical, and microstructural properties of wood ashes are significant. All ashes must be properly tested before their use as a construction material.
- Most wood ashes do not strictly conform to ASTM C 618 requirements for coal fly ash.
- LOI and alkali contents of wood ashes are generally greater than those found in coal ashes.
- Based on the properties of wood ash, several potential applications of wood ash exist in cement-based materials including CLSM, low- and medium-strength concrete, cast-concrete products, RCCP, road base course materials, and blended cements.
- The results revealed that wood ash can be used as a component of CLSM and structural-grade concrete.
- Wood ash containing CLSM can be used as both excavatable and non-excavatable fill material.

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Table 1- Gradation of Wood Ash

Fly Ash			Bottom Ash			ASTM C 33 for Sand
% Passing			% Passing			% Passing
Sieve Size	Average	Range	Sieve Size	Average	Range	
3/4" (19.1-mm)	98.8	91.8-100	1" (25.4-mm)	99.6	98.4-100	100
1/2" (12.7-mm)	97.0	81.5-100	3/4" (19.1-mm)	-	-	100
3/8" (9.5-mm)	93.2	73.1-100	1/2" (12.7-mm)	82.0	67.9-84.3	100
#4 (4.75-mm)	87.7	60.3-100	3/8" (9.5-mm)	80.0	61.8-90.6	100
#8 (2.36 mm)	83.1	50.1-100	#4 (4.75-mm)	65.9	49.9-84.2	95-100
#16 (1.18 mm)	75.0	37.3-99.5	#8 (2.36 mm)	49.0	30.3-76.6	80-100
#30 (600 μm)	60.9	19.2-99.2	#16 (1.18 mm)	35.5	15.9-68.3	50-85
#50 (300 μm)	50.5	8.0-97.5	#30 (600 μm)	25.7	7.8-57.3	25-60
#100 (150 μm)	41.4	16.0-90.8	#50 (300 μm)	18.5	3.7-45.0	10-30
			#100 (150 μm)	11.4	2.1-27.9	2-10

Table 2 - Chemical Analysis Data for Wood Ash

Analysis Parameter	Fly Ash		Bottom Ash		ASTM C 618		
	Average (%)	Range (%)	Average (%)	Range (%)	Class N	Class C	Class F
Silicon Dioxide, SiO ₂	26.5	4.0-59.3	42.3	32.2-50.7		-	-
Aluminum Oxide, Al ₂ O ₃	9.0	5.0-17.0	17.9	15.5-20.3		-	-
Iron Oxide, Fe ₂ O ₃	5.4	1.0-16.7	12.6	4.7-20.8		-	-
SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃	40.7	10.0-72.2	73.8	56.9-93.4	70 Min	50.0 Min	70.0 Min
Calcium Oxide, CaO	16.0	2.2-36.7	11.4	4.2-22.2		-	-
Magnesium Oxide, MgO	3.0	0.7-6.5	2.5	0.9-4.8		-	-
Titanium Oxide, TiO ₂	0.51	0.0-1.2	1.0	0.7-1.5		-	-
Potassium Oxide, K ₂ O	5.0	0.4-13.7	1.3	0.5-2.2		-	-
Sodium Oxide, Na ₂ O	1.7	0.5-14.3	0.9	0.5-1.3		-	-
Sulfate, SO ₃	4.8	0.1-15.3	0.4	0.1-0.7	5.0 Max	5.0 Max	5.0 Max
Loss on Ignition, LOI	23.4	6.7-58.1	9.9	1.4-33.2	10.0 Max	6.0 Max	6.0 Max.*
Moisture Content	2.6	0.1-21.5	0.6	0.2-0.9	3.0 Max	3.0 Max	3.0 Max
Available Alkali, Na ₂ O Equivalent (ASTM C 311)	3.3	0.4-20.4	N. A.	N. A.	1.5 Max	1.5 Max.**	1.5 Max.**

* Under certain circumstances, up to 12% max. may be allowed

** Optional, required for ASR minimization.

N. A. = Not Available

Table 3- Concrete Mixture Proportions

Mixture Proportions	Control Mixture	Mixture Containing 25% Wood Ash	Mixture Containing 25% Wood Ash and Coal Fly Ash	Mixture Containing 35% Wood Ash and Coal Fly Ash
Cement (lb/yd ³)	557	460	460	400
Wood Ash (lb/yd ³), A ₁	-	150	75	105
Fly Ash (lb/yd ³), A ₂	-	-	75	105
Water, (lb/yd ³)	278	330	290	290
[W/(C+ A*)]	0.50	0.55	0.47	0.48
SSD Fine Aggregate (lb/yd ³)	1380	1380	1380	1370
SSD Coarse Aggregate (lb/yd ³)	1810	1680	1685	1690
Slump (in)	3-1/2	4	3-1/2	3-1/2
Air Content (%)	1.3	1.4	1.1	1.8
Air Temperature (°F)	81	76	78	80
Concrete Temperature (°F)	82	77	78	81
Fresh concrete Density, (lb/yd ³)	149	148	147	147

$$A^* = A_1 + A_2$$

Table 4-Compressive and Splitting Tensile Strength of Concrete

Mixtures	Compressive Strength, (psi)					Split Tensile Strength (psi)				
	3 days	7 days	14 days	28 days	91 days	3 days	7 days	14 days	28 days	91 days
Control Concrete	3230	4350	5035	5380	6110	420	520	575	590	685
Concrete Containing 25% Wood Ash	2490	3500	4300	5000	6015	350	395	495	500	635
Concrete Containing 25% Wood Ash and Coal Fly Ash	2940	4430	5120	5805	7175	310	400	530	570	720
Concrete Containing 35% Wood Ash and Coal Fly Ash	2735	3395	4730	5150	7270	300	380	500	565	725

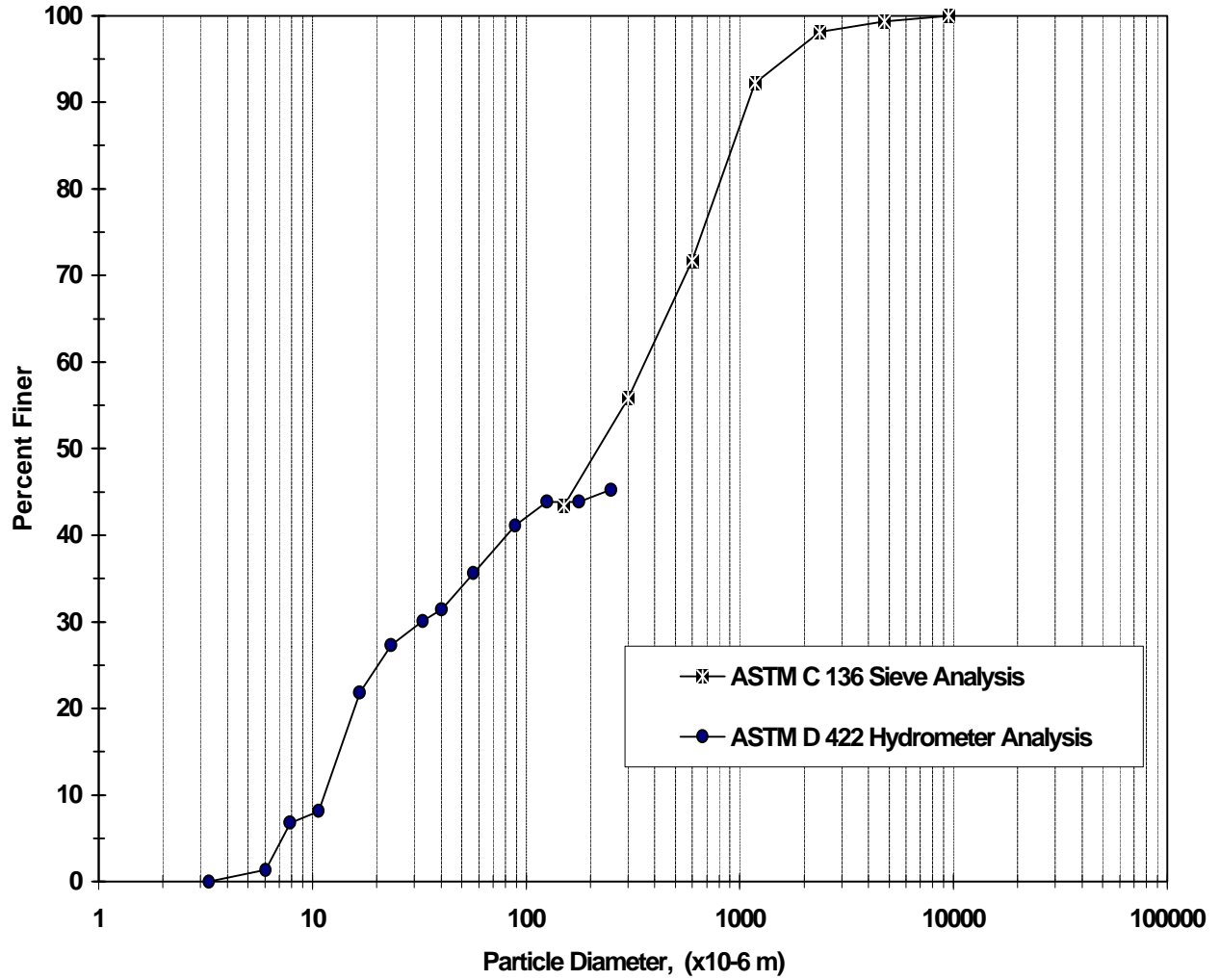
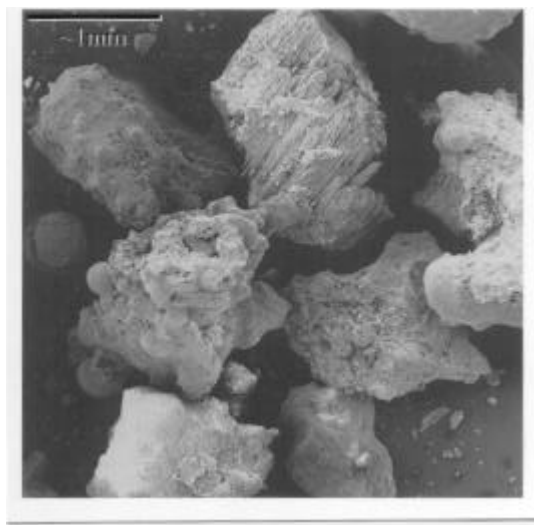
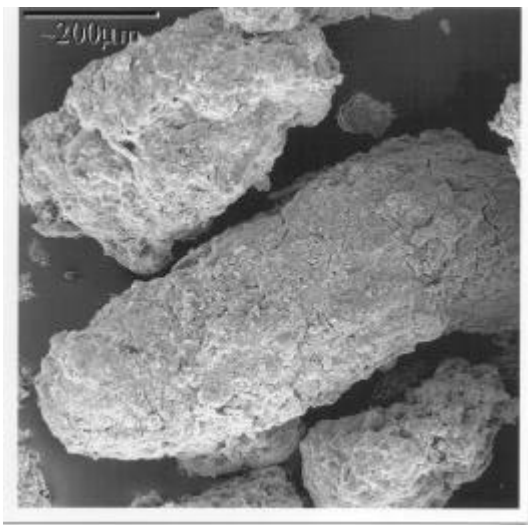
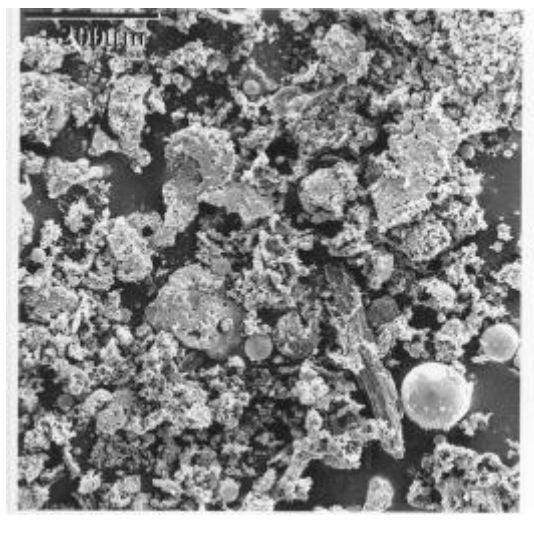


Fig. 1 - Particle size distribution of a typical wood fly ash



Bottom Ash



Fly Ash

Fig. 2 - Micrographs of wood ash

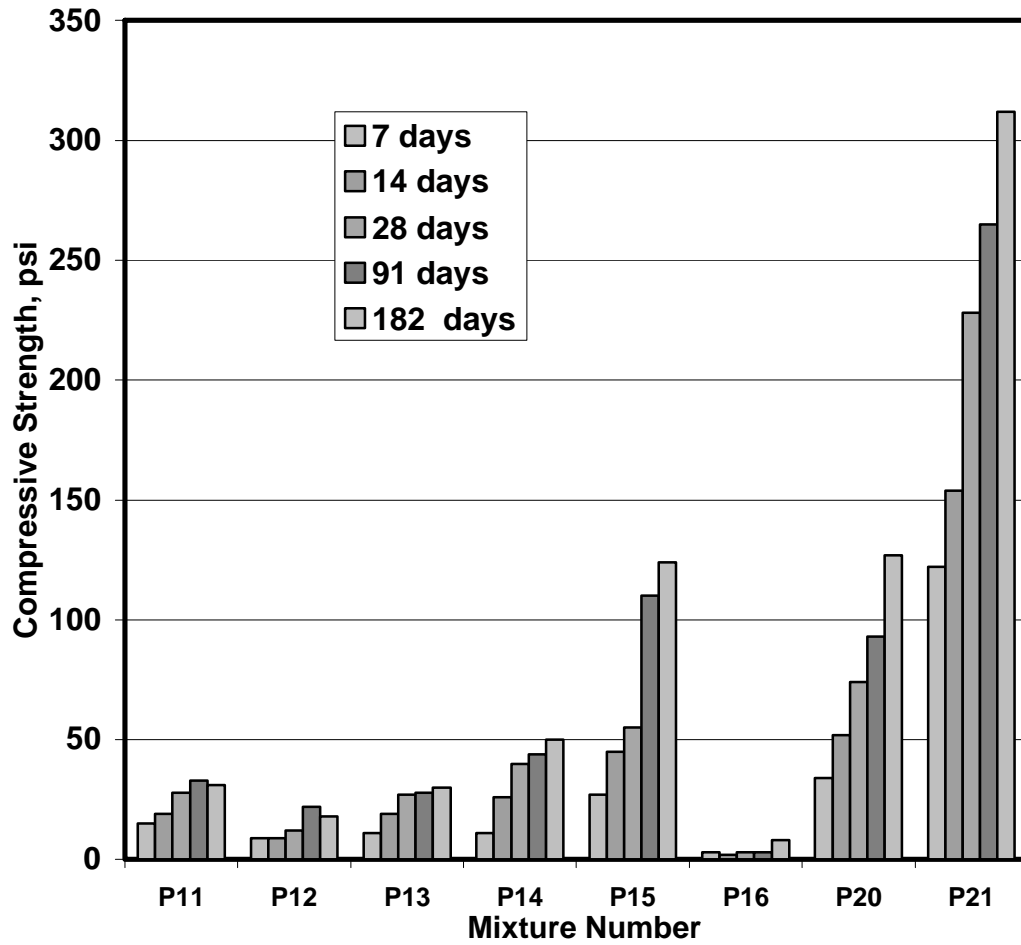


Fig. 3 - Compressive strength of CLSM mixtures containing wood ash