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EFFICACY OF FOREST BASED ASH AS A SUPPLEMENTARY CEMENTING MATERIAL FOR CONCRETE

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2 **EFFICACY OF FOREST BASED ASH AS A SUPPLEMENTARY CEMENTING MATERIAL FOR**

3 **CONCRETE**

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12 **Abstract**

13 This paper presents a feasibility study on the effects of

14 forest-based ash (FBA) on the mechanical performance of concrete. Four such samples were

15 obtained from the pulp and paper industry as the residual byproduct of their hog fuel. They were

16 analysed for grain size distribution, density, morphology and oxide content. Subsequently, the ash

17 was employed as a cement substitute (up to 20% by mass) and the resulting concrete was examined

18 for mechanical properties. Results show that all four FBA samples were coarser than Portland

19 cement with mean particle size around 100-1000 microns. Further, X-ray florescence showed that

20 the FBA samples were predominantly composed of CaO, with significant amounts of SO₃ and

21 alkali oxides at levels which exceed maximum limits allowed for the latter by ASTM. This poses

22 concerns on durability. Nevertheless, based on short term compressive and tensile performance

23 alone, this study shows that FBA could replace up to 15% by mass of cement.

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Introduction

The work reported here is a study conducted to ascertain the mechanical performance of concrete containing samples of forest based ash (FBA) as a supplementary cementing material towards partial replacement of Portland cement. The FBA was obtained by burning forest wood barks – both hard and soft wood – and other wood residues, that are deemed a waste and so used as hog fuel by the pulp and paper industry across Alberta in Western Canada. This study focused firstly, on characterizing the ash samples for physical and chemical properties and secondly, on the short term mechanical performance of concrete made with the ash as a supplementary cementing admixture.

The possibility of gainfully using agricultural wastes in concrete mixtures, both to solve the waste disposal problem and to get a cost advantage in concrete production, has caught the attention of researchers in the last couple of decades. Accordingly, sugarcane bagasse ash (SCBA), rice husk ash (RHA) and coconut husk ash (CHA) have variously been examined for their pozzolanic potential (Rabi et al. 2009; Paula et al. 2010; Fairbairn et al. 2012). In all cases, results from tests with mortars indicate the viability of partial substitution of cement by up to 20% of the ash considered. Chusilp et al. (2009) reported that sugarcane bagasse ash when used as a pozzolanic material in concrete imparts acceptable strength, lower heat evolution, and a reduced water permeability with respect to the reference mixture containing Portland cement only. Concrete containing 20% ground bagasse ash had the highest compressive strength at over 110% of the reference mixture (Srinivasan et al. 2010; Radke et al. 2012). Further, Castaldelli et al. (2013) reported SCBA as a feasible starting material for preparing alkali-activated geopolymers.

With rice husk ash, cement replacement at between 10-20% depending on mixture design, led to higher compressive strength in concrete (Ramasamy 2010; Foletto et al. 2006 and Ganesan et al. 2008). Similarly, Ramezani pour et al. (2009) showed that concrete incorporating RHA resulted in higher compressive strength, higher tensile strength and superior modulus of elasticity at various ages compared with that of the reference unblended concrete.

There appears to be limited information available on the potential for ash sourced from using forest wastes such as wood barks and low quality wood chips (Chowdhury et al. 2014 and Grau et al. 2015). The mixture of bark, low quality wood chip shavings, sawdust and other wood waste which are burned as fuel by pulp mills is called “hog fuel”. The composition of hog fuel is not well defined and it depends upon the local wood species and the presence of wood based industries such as saw mills and pulp mills. A considerable amount of such ash is produced in Alberta when wood bark and chips that are deemed as lower quality and hence unfit for use in the pulp and paper industry, are used instead as fuel. Therefore, this study was undertaken principally to assess the effect of using such ash as a pozzolanic admixture in concrete. Four samples of forest based ash (FBA) sourced from the pulp and paper industry in Alberta were examined. These samples were first characterized for their physical properties and chemical composition and thereafter, incorporated as partial replacement of Portland cement in concrete to examine their effect on the key mechanical properties of concrete.

Experimental Procedures

Concrete cylinders were prepared with varying amounts of forest based ash. Four different types of ash derived from burning forest waste in Alberta’s pulp and paper mills were used. For each

type of FBA, Portland cement was replaced at 5 to 20% by mass in 5% intervals. A reference mixture was also prepared containing only Portland cement, sand, aggregates and water. Thus, in all, seventeen mixtures were examined and the samples were subjected to compression and split tension tests.

Constituent Materials

Type GU Portland cement conforming to CSA A3001-13 (ASTM C150), locally available coarse aggregate and sand conforming to ASTM C33 were used to prepare the concrete specimens in this study. The salient properties of these materials were as follows: The Type GU cement had a bulk density of 1450 kg/m^3 ; the maximum particle size for the coarse aggregate was 8 mm and its bulk density was 1710 kg/m^3 ; the fine aggregate had a bulk density of 1900 kg/m^3 and the four types of forest based ash namely, FBA 1 through FBA 4 had a respective bulk density of 405 kg/m^3 , 520 kg/m^3 , 470 kg/m^3 and 320 kg/m^3 . The forest based ash samples were created by firing the hog fuel while generating heat and steam at pulp mills. Hog fuel generally comes from a variety of sources—sawmill bark (mostly softwood), hardwood bark and scraps from the bush that result from the chipper operations, old hay from surrounding farms and, fibres from the effluent clarifier (ie. both primary and secondary sludge). In general, there is always considerable variability in the biological source for forest based ash. The best that one can ascertain is that the source vegetation came from within the Province of Alberta. The forest based ash samples were obtained after burning the aforementioned waste as fuel in the paper mills at between $400\text{-}470^\circ\text{C}$.

91 **Preparation of Fresh and Hardened Concrete Specimens**

92 The mixtures were designed to achieve a compressive strength of 30 MPa at 28 days and a
93 workability corresponding to a slump of 25-50 mm. The water to cement ratio was selected at 0.5
94 and the mixture proportions are listed in Table 1. The target slump was not high since this study
95 was also intended to compare with a series containing sugarcane bagasse ash for applications in
96 India (Setayeshgar 2015). Concrete cylinders of length 150 mm and 75 mm diameter were cast.
97 As shown later, the mean particle size for all samples of ash was found to be one order of
98 magnitude bigger than that for Portland cement. Hence, it was deemed better to let the ash mix
99 with the rest of the dry constituents, ahead of introducing water. Accordingly, the coarse aggregate
100 was first poured in the mixer and then sand, cement and ash were added in that order and mixed
101 firstly as dry powder in the mixer for 2 minutes. Subsequently, the amount of water per the mix
102 design was added to the dry mixture and the resulting mixture was agitated together for a further
103 2 minutes. The assembled molds were filled with the cement concrete mixture in 3 layers and
104 compacted using a table vibrator. The cylinders were removed from the molds after 24 hours of
105 casting and cured until 28 days in a controlled environment chamber maintaining a humidity of
106 100% and a temperature of 23 ± 2 °C. The concrete specimens were designated CFBA in order to
107 distinguish them from the ash contained therein (FBA).

108

109

110 **Testing of Fresh and Hardened Concretes**

111 For each mixture prepared, the slump and air content were evaluated as per ASTM C143 and
112 ASTM C231, respectively. The concrete cylinder in compression was instrumented with lateral

and vertical LVDTs that were in turn connected to a data acquisition system with 1 Hz frequency. Thus, the modulus of elasticity and the Poisson's ratio were evaluated alongside. The compression test was per ASTM C496 while the splitting tension test was done as per ASTM C469.

Results and Discussion

Physical and Chemical Characterization of FBA

The bulk density of these four samples of FBA were evaluated prior to mixing and have already been listed above. The samples were analyzed for grain size distribution using a laser diffraction mastersizer followed by scanning electron microscopy (SEM) to examine their morphology. Chemical characterization involved identification and quantification of the constituent oxides, through energy-dispersive X-ray spectroscopy (EDX), X-ray diffraction (XRD) and X-ray fluorescence (XRF).

Figure 1 shows the X-ray diffraction traces (XRD) of the four different types of FBA used in this study. Table 2 summarizes the various oxides found in these FBA samples. While there is no standard that pertains directly to the cementing ability of forest based ash, a guideline is offered through ASTM C618 (2013), wherein certain performance based limits are placed on the composition. In particular, given the high CaO content of the FBA samples seen in this study, a comparison is made with Class N Pozzolan and Class C Fly Ash. These limits are captured in Table 2, alongside the oxide composition of the FBA samples from this study. Note that the sum of the key acidic oxides namely, silica, alumina and iron oxides in the four samples of FBA examined here is lower than the minimum allowable amount, per ASTM C618. On the other hand, the FBA samples had higher alkali content ($\text{Na}_2\text{O} + \text{K}_2\text{O}$) and higher SO_3 content than the limits

imposed in ASTM C618. The present findings echo those seen by others (Etiegne and Campbell 1991; Naik et al. 2001; Udoeyo et al. 2006; Abdullahi 2006). All four FBA samples revealed high CaO content and FBA 4 had over 60% CaO. While the range of possible oxide content from Alberta's pulp mills is currently being examined by the authors, the present study indicates that as against being strictly pozzolanic, the FBA is likely latent hydraulic in nature with weak pozzolanic reactivity.

Also, the presence of alkalis exceeds the allowable maximum limit. That may result in triggering alkali-silica reaction with susceptible aggregates. However, Zerbino et al (2012) noted that if the ash particles were smaller than 75 microns, the potential of alkali silica reaction would be significantly minimized, making the ash suitable for concrete application. Further, it was seen that in all four cases (FBA 1 through 4), the chemicals portlandite, arcanite, quartz and calcite exhibited distinct peaks as compared to the other minerals. The XRD output shows that among the constituent phases, quartz and calcite have maximum crystallinity. Some of the minerals identified are the same as that for the Portland cement clinker such as arcanite. Others are the same as seen in blended Portland cement, such as calcite, quartz and hematite. Still others resemble those found in hydration products, such as portlandite (Aranda et al. 2012). As expected, only the crystalline phases were detected through XRD. In order to detect the amorphous constituents and quantify the oxides identified, EDX and XRF were done.

Table 3 shows the percentage of various elements that were found through EDX tests in the four different samples of forest based ash: FBA 1, FBA 2, FBA 3 and FBA 4. In each case, the Calcium, Oxygen and Carbon are dominant, suggesting the presence of $\text{Ca}(\text{OH})_2$ and $\text{Ca}(\text{CO}_3)$. Further, significant amounts of potassium and silicon were found. It may be inferred that the minerals

portlandite, arcanite, calcite and quartz appear to be more predominant than the other minerals listed.

Results by previous researchers (Folletto et al. 2006; Larbi et al. 2010; Ramesanianpour et al. 2009) show that the main constituent in rice husk ash is silica, typically 85-88%; that RHA also contains some minor oxides such as alkalis, sulphate and portlandite. Similarly, in SCBA, silica is the most predominant oxide (Paya et al. 2002). Such studies also showed that the silica remained in the amorphous form at temperatures between 450-700°C for 3 to 4 hours of husk burning. Since the crystalline forms of silica have less reactivity than the amorphous one, it is essential that rice husks burnt under temperature of 850°C. In Alberta's pulp and paper mills, the burning temperature of forest based ash is around 400-470°C.

In order to understand the source composition of the hog fuel, an elemental analysis on forest based ash from Finland was referred to (Sarela et al. 2005). That study, summarized in Table 4, includes bark and wood from birch, spruce and pine - all very common to Alberta's forest as well. The compositions of other likely hog fuel sources such as old hay from surrounding farms or fibres from the effluent clarifier (primary and secondary sludge) are not listed. The K/Na elemental ratios for FBA samples in this study is shown in Table 5. Comparing between Tables 4 and 5, it can be argued that FBA 4 has the least and FBA 2 has the most bark constituents. It also implies that FBA 3 was second in terms of bark constituents.

Further, the ash samples were examined under a Scanning Electron Microscope to observe the size and morphology of the constituent particles. It is seen from the micrographs in Figure 2 that most

179 particles were larger than 100 microns. Whereas particles in FBA 1 were mostly spherical, those
180 in FBA 2 were variously spongy or shaped like needles. Particles of FBA 3 were both spherical
181 and sometimes flat as sheets and finally in FBA 4, the particles were seen to be variously spherical,
182 spongy and arranged into sheets.

183 The ash samples were analyzed for grain size distribution using a mastersizer instrument. This
184 device employs laser diffraction and measures the particle size distribution through the angular
185 variation in the intensity of light scattered when a laser beam passes through a dispersed particulate
186 sample. The angular scattering intensity is then analyzed to calculate the size of the particles
187 responsible for creating the scattering pattern.

188 It is clear from Figure 3, that ash samples FBA 1 and FBA 4 were somewhat finer than the other
189 two namely, FBA 2 and FBA 3. Among them, FBA 1 was the finest and FBA 2 was the coarsest
190 in particle size distribution. One can explain the particle size based on the composition of ashes.
191 When the biomass power plants with wood and wood residues came into operation, fouling of
192 convection passes and severe deposits on grates and in fluidized beds were observed, due to
193 stickiness of particles. These wood residues, particularly bark, characteristically contain high
194 levels of potassium and other alkalis. They vaporize or react with other elements as they pass
195 through the boiler, partially condensing from the liquid phase and growing to form sticky deposits
196 on metal and refractory surfaces (Miles et al. 1996). The effect of chemical composition, in
197 particular potassium, sodium and chloride on the stickiness of ash deposits were analyzed in the
198 case of wood residues from kraft pulping (black liquor) firing (Reeve et al. 1983).

199 Note from Table 3, that when the elemental analysis was conducted across all samples, the
200 potassium content for FBA 4 was too low to register. The same was confirmed alternatively

through XRF whereby as listed in Table 2, it is noted that the lowest K_2O content was with FBA 4. In addition to the molar ratio between K and Na, Table 5 presents also the mean particle size as observed in the four FBA samples. From Table 4, note that typically, bark has a K/Na ratio of 26 while wood has a corresponding ratio of 13. Particle stickiness has been well studied in kraft recovery boilers (Reeve et al. 1988). Those studies indicate that increasing the mole ratio of $K/(Na+K)$ leads to a drop in the melting point of the ash particles and so makes them sticky. This in turn leads to adhesion and particle growth. Since bark is potassium rich, it is always desirable to control the bark content in the hog fuel to minimize the $K/(Na+K)$ ratio and in turn reduce the mean particle size. An excess of bark in the hog fuel therefore leads to more stickiness among the particles that consequently results in coarser particle size distribution. Among the ash samples here, FBA 4 had the least K/Na ratio while FBA 2 had the highest K/Na ratio. This ties in with the particle size distribution shown in Figure 3.

Note that all four ash samples here were significantly coarser than Portland cement. On the other hand, various other agro-sourced ash have been seen to be finer in comparison. For instance, the particle size distribution in SCBA was between 1-100 μm with mean size at 35 μm (Paya et al. 2002; Ganesan et al. 2007) while -rice husk ash is typically between 1 to 8 μm (Yuzer 2013; Shatat 2014). The finer the particles, the better the pozzolanic efficiency. The authors are in discussion with pulp and paper mills in order to further explore the possibility for engineering the particle size distribution for FBA through suitable choice of hog fuel composition. For the present, after examining the results of the physical and chemical analysis of the ash samples alone, FBA 4 was thought to be best suited of the four FBA samples when used as a supplementary cementing material.

224 **Properties of Fresh Concretes**

225 Table 6 lists the slump and air content as measured for the fresh concrete prepared with the
226 different amounts of each type of FBA. As seen therein, FBA 1, FBA 2 and FBA 3 did not
227 adversely affect the slump. Perhaps due to its predominantly spherical particles, higher amounts
228 of FBA 1 leads to an increase in the slump. Whereas FBA 2 and FBA 3 had coarser particle size
229 distribution and were seen to increase the slump at low dosage, the predominantly non spherical
230 shape of their particles likely leads to a progressive reduction in slump at higher dosage. Note from
231 Figure 3 and Table 5 that of the four ash samples, FBA 4 had the smallest mean particle size. Also,
232 it was rich in CaO content, so that it was more likely than others to readily hydrate. All of which
233 is reflected in the decrease in slump recorded with this ash sample. As seen further in Table 6, the
234 four FBA samples did not adversely affect the air content in fresh concrete. While outside the
235 scope of the present study, it is nevertheless imperative in order to ensure freeze-thaw resistance
236 that further quantification of air content be made as the concrete matures in order to verify the
237 stability of the air-void network.

238 **Properties of Hardened Concretes**

239 **Compressive Strength**

240 The compressive strength for each mixture as evolving over 28 days of curing is listed in Table 7.
241 This data is plotted in Figure 4 to reflect the evolution with time. Figure 5 shows the compressive
242 strength at 28 days for the various mixtures examined here. It appears that of the four samples of
243 ash investigated here, FBA 4 imparts the highest strength to the concrete at 28 days. Note that the
244 compressive strength of mixtures containing FBA 4 is more than or equal to that of the reference
245 mixture up to 15% cement replacement. On the other hand, FBA 3 did not significantly alter the

compressive strength when replacing Portland cement by up to 15% by mass. However, in case of FBA 1 and FBA 2, the strength drops considerably – between 20-30% with respect to the reference mixture containing Portland cement alone – even at 5% cement replacement. Even so, a dramatic drop was observed only beyond 15% mass replacement. When comparing the present findings with those from the literature, it should be borne in mind that the hog fuel composition is specific to the source vegetation and local soil composition. As stated earlier, this in turn plays an important role in oxide content of the resultant FBA. Nonetheless, studies by Udoeyo et al. (2006), Naik et al. (2001) and Abdullahi (2006) reveal a drop in compressive strength with an increase in the ash content. Yet, a blend of equal amounts of forest based ash and fly ash from coal-fed thermal power plants appears to increase the compressive strength for total ash content up to 35% of the binder (Naik et al. 2001). In all these studies, it is clear that between 10-15% by mass of Portland cement may be replaced with FBA. Beyond this dosage, a more rapid decrease in strength is seen.

Tensile Strength

The splitting tensile strength of the mixtures as ascertained per ASTM C496 (2011) is listed in Table 8. As with the compression data, the evolution of strength over a 28 day curing period is shown in Figure 6. Further, the 28-day strength as evaluated with varying amounts of FBA is shown in Figure 7 for each ash sample. Unlike with compressive strength wherein smaller amounts of FBA 3 or FBA 4 led to an increase over that of the reference mixture, in case of tensile strength, the addition of FBA was seen to decrease it for all four ash samples. Others have found similarly that the tensile strength drops with introducing FBA into concrete. Nevertheless, as seen with their performance under compression, here too FBA 4 was the best performing ash with lower drops in tensile strength as compared to the reference mixture. Once again, Naik et al. (2001) noted an increase in tensile strength when the forest based ash is blended with fly ash up to a total of 35% in the binder.

Modulus of Elasticity and Poisson's Ratio

The modulus of elasticity, E_c , and the Poisson's ratio, μ , were evaluated at 28 days, together with the compressive strength per ASTM C469 (2014). The data is listed in Table 9 and the modulus of elasticity is plotted in Figure 8. Not surprisingly, the modulus of elasticity mimics the performance under splitting tension. On the one hand, note that FBA 2 was the coarsest with the lowest CaO content and, this may be linked to consistently lower tensile strength as well as elastic modulus. It is likely that the coarser particle size in all the FBA, as opposed to that of Portland cement, leads to a weaker interfacial transition zone that is more perceptible with tensile strength and the elastic modulus but is less so with compressive strength. Of the four samples examined

here, two factors likely contribute to the superior performance of FBA 4. First, this ash sample possessed the lowest mean particle size. Second, FBA 4 also had higher CaO content. Together, the two likely contribute to latent hydraulic and weak pozzolanic reactivity.

As stated earlier, the authors could not ascertain precisely the origin of the biomass that led to these ash samples, other than that they are from Alberta based forests. Nevertheless, the ash samples were examined for physical properties and chemical composition. Subsequently, they were incorporated as a cement substitute into concrete mixtures that were further evaluated for fresh and hardened properties. Although long term durability was outside the scope of this study, the levels of alkali oxides, specifically Na_2O and K_2O found in this study strongly compels a concerted investigation on forest based ash for their alkali-silica reactivity before recommending them unreservedly for utilization in concrete. Nonetheless, based on the results of this study, the specific findings are as follows:

1. The particle size analysis shows that all four samples of ash had mean particle size larger than 100 microns and so, they were about one order of magnitude coarser than Portland cement. A variety of particle shapes could be identified.
2. The forest based ash samples have a higher CaO content when compared with conventional coal-based fly ash. At the same time, they had higher alkali content but lower acidic oxide content than is acceptable in coal-based fly ash or Class N pozzolan. Specifically, as the ratio of $K/(K+Na)$ relates to the stickiness of the ash particle, a correlation was found between this ratio and the mean particle size. Of the four samples, FBA 4 was seen to have the highest CaO content and among the finest particle size distribution.
3. When used as a cement substitute, FBA 4 performed most efficiently among the four ash samples, across all mechanical parameters evaluated here. An optimal dosage was found to be 10-15% of cement replacement.

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Table 1- Mixture Proportions of Concretes

FBA/Binder Content	Cement(kg/m ³)	FBA(1,2,3,4) (kg/m ³)	Water(kg/m ³)	Sand(kg/m ³)	Coarse Aggregate(kg/m ³)
0%	400	0	200	600	1200
5%	380	20	200	600	1200
10%	360	40	200	600	1200
15%	340	60	200	600	1200
20%	320	80	200	600	1200

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Table 2- Chemical Composition of Forest Based Ashes (ASTM C618, Bye 1999)

Oxide:	FBA 1	FBA 2	FBA 3	FBA 4	Portland cement	Pozzolan Class N	Fly Ash Class C
	Average Wt%	Average Wt%	Average Wt%	Average Wt%	Wt%	allowable Wt% limit	allowable Wt% limit
Al ₂ O ₃ +Fe ₂ O ₃ +SiO ₂	15.23	18.66	13.34	3.85	23.00-34.50	Min 70.00	Min 50.00
Alkalies (K ₂ O, Na ₂ O)	12.39	15.85	16.23	8.10	0.17-1.60	Max 1.50	
Na ₂ O	2.45	1.92	2.99		0.07-0.40		
MgO	5.81	3.45	5.21	1.94	0.50-2.50		
Al ₂ O ₃	1.98	2.50	1.78	0.53	3.00-7.00		

SiO ₂	11.88	14.31	10.31	2.31	19.00-23.00		
P ₂ O ₅	4.09	3.16	3.60	3.43			
SO ₃	25.60	28.03	31.02	18.47	2.50–3.50	Max 4.00	Max 5.00
K ₂ O	9.94	13.93	13.24	8.10	0.10-1.20		
CaO	36.00	29.99	29.72	63.03	63.00–67.00		
TiO ₂	0.22	0.28	0.19	0.22			
MnO	0.18	0.19	0.16	0.24			
Fe ₂ O ₃	1.37	1.85	1.25	1.01	1.50-4.50		
Ni ₂ O ₃	0.02	0.01	0.01				
CuO	0.02	0.01	0.01	0.02			
ZnO	0.30	0.23	0.39	0.50			
Br ₂ O	0.01	0.01	0.01	0.02			
SrO	0.12	0.12	0.11	0.13			

Table 3- EDX Test Results of FBA Samples

Elements	FBA 1 (wt %)	FBA 2 (wt %)	FBA 3 (wt %)	FBA 4 (wt %)
O	21.58	21.06	52.97	36.63
K	4.78	3.92	7.02	N/A
S	1.20	0.96	2.58	1.46
Al	0.14	0.05	1.35	0.18
P	0.26	0.12	0.64	0.25
Cl	0.33	N/A	0.24	N/A
Ca	7.11	4.70	26.44	10.11
Si	0.36	0.25	4.59	0.45
Mg	0.66	0.34	1.95	0.96
Na	0.87	0.15	0.86	0.51
C	62.65	N/A	N/A	N/A
Fe	N/A	N/A	1.08	0.08

Table 4- Typical Element Composition of Ash Sources of Pine Bark and Wood (Saarela et al. 2005)

Elements	S	Ca	K	Mg	P	Fe	Mn	Al	Na
Bark (%)	N.A.	0.7300	0.2500	0.1100	0.0650	0.0060	0.0900	0.0110	0.0096
Wood (%)	N.A.	0.0650	0.0430	0.0130	0.0040	0.0009	0.0200	0.0009	0.0032

Table 5 – Elemental Mass Ratio of Potassium and Sodium in Forest Based Ash and a Comparison with Particle Size

	FBA1	FBA2	FBA3	FBA4
Na (%)	0.87	0.15	0.86	0.51
K (%)	4.78	3.92	7.02	0
Mole K/(Na+K)	0.84	0.96	0.89	0.0
K/Na	5.50	26.10	8.20	~0
Mean Particle Size(Micro Meter)	~300	~1000	~1000	~400

Table 6- Fresh Properties of Concrete Mixtures

	Reference	CFBA 1 %				CFBA 2 %				CFBA 3 %				CFBA 4 %			
		5	10	15	20	5	10	15	20	5	10	15	20	5	10	15	20
Slump (mm)	27	24.0	33.0	32.5	33.0	49.0	35.0	27.0	25.0	40.0	30.0	27.0	27.0	25.0	20.0	27.0	20.0
Air Content (%)	2.5	2.7	2.6	2.6	3.5	3.4	4.5	3.7	3.7	3.4	3.3	3.8	3.7	2.9	3.3	3.5	3.5

Table 7- Compressive Strength of Concrete Mixtures

	Percentage of FBA (%)	Average Compressive Strength [N/mm ²] (Std. Dev.)				
		1 Day	3 Days	7 Days	14 Days	28 Days
CFBA1	0	17.36 (0.49)	27.27 (0.49)	32.24 (0.48)	33.00 (0.50)	33.14 (0.54)
	5	11.75 (0.22)	20.36 (0.21)	25.00 (0.25)	31.74 (0.24)	27.92 (0.23)
	10	5.69 (0.32)	15.76 (0.33)	18.00 (0.31)	22.00 (0.34)	24.50 (0.35)
	15	13.00(0.4)	17.00 (0.43)	23.82 (0.41)	26.74 (0.45)	28.57 (0.47)
	20	9.00(0.17)	10.00 (0.16)	17.78 (0.19)	19.25 (0.18)	22.75 (0.18)
	5	9.52 (0.27)	16.00 (0.29)	21.78 (0.26)	22.48 (0.27)	24.55 (0.28)

CFBA 2	10	6.32 (0.26)	19.88 (0.25)	24.26 (0.23)	23.65 (0.24)	27.12 (0.25)
	15	15.31 (0.35)	16.60 (0.32)	20.50 (0.33)	22.55 (0.3)	23.50 (0.37)
	20	10.30 (0.10)	11.82 (0.11)	14.46 (0.08)	14.31 (0.09)	16.30 (0.1)
CFBA 3	5	12.18 (0.15)	21.79 (0.14)	27.91 (0.16)	28.04 (0.14)	35.00 (0.15)
	10	11.50 (0.32)	23.57 (0.33)	25.35 (0.32)	29.60 (0.31)	31.72 (0.32)
	15	12.50 (0.21)	20.54 (0.22)	24.00 (0.23)	25.84 (0.21)	30.33 (0.22)
	20	10.27 (0.20)	18.10 (0.22)	20.00 (0.21)	22.51 (0.20)	25.00 (0.21)
CFBA 4	5	14.00 (0.14)	28.00 (0.16)	31.00 (0.15)	34.00 (0.14)	42.50 (0.15)
	10	16.52 (0.10)	24.12 (0.12)	28.18 (0.11)	32.50 (0.09)	38.30 (0.10)
	15	14.81 (0.14)	24.70 (0.14)	27.00 (0.13)	29.83 (0.15)	29.00 (0.14)
	20	12.58 (0.17)	22.00 (0.17)	22.28 (0.16)	27.75 (0.18)	30.00 (0.17)

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Table 8- Tensile Strength of Concrete Mixtures

	Percentage of FBA (%)	Average Tensile Strength [N/mm ²] (Std. Dev.)				
		1 Day	3 Days	7 Days	14 Days	28 Days
CFBA 1	0	2.04 (0.02)	3.26 (0.02)	3.52 (0.01)	3.57 (0.02)	3.63 (0.02)
	5	1.75 (0.11)	2.71 (0.10)	3.24 (0.08)	3.36 (0.09)	3.56 (0.10)
	10	1.00 (0.11)	2.31 (0.09)	2.61 (0.09)	2.75 (0.1)	2.83 (0.11)
	15	0.80 (0.09)	2.50 (0.09)	2.58 (0.08)	2.59 (0.09)	3.10 (0.08)
	20	0.70 (0.08)	1.89 (0.09)	2.17 (0.12)	2.16 (0.1)	2.49 (0.11)
CFBA 2	5	1.38 (0.10)	2.48 (0.12)	2.58 (0.10)	2.93 (0.09)	2.97 (0.11)
	10	1.59 (0.02)	2.98 (0.01)	2.43 (0.02)	2.97 (0.01)	2.96 (0.02)
	15	1.84 (0.05)	1.87 (0.05)	2.62 (0.04)	2.68 (0.06)	2.28 (0.05)
	20	1.41 (0.08)	1.65 (0.09)	2.33 (0.11)	2.19 (0.1)	1.80 (0.12)
CFBA 3	5	1.88 (0.08)	2.64 (0.07)	2.97 (0.06)	2.81 (0.08)	3.16 (0.07)
	10	1.87 (0.08)	2.93 (0.07)	3.00 (0.08)	3.20 (0.07)	3.04 (0.08)
	15	1.62 (0.08)	2.31 (0.09)	2.46 (0.06)	2.30 (0.07)	3.08 (0.08)
	20	1.44 (0.10)	2.10 (0.09)	2.18 (0.08)	2.12 (0.09)	2.89 (0.10)
CFBA 4	5	1.61 (0.10)	2.81 (0.11)	2.67 (0.11)	3.22 (0.10)	3.61 (0.12)
	10	1.67 (0.10)	2.64 (0.12)	2.89 (0.11)	3.15 (0.10)	3.63 (0.12)
	15	1.40 (0.10)	2.43 (0.09)	2.54 (0.12)	2.91 (0.11)	3.34 (0.11)
	20	1.53 (0.08)	2.34 (0.09)	2.74 (0.07)	2.96 (0.08)	3.49 (0.07)

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Table 9- Modulus of Elasticity and Poisson’s Ratio of Concrete Mixtures

FBA (%)	CFBA 1		CFBA 2		CFBA 3		CFBA 4	
	E(GPa)	μ	E(GPa)	μ	E(GPa)	μ	E(GPa)	μ
	(Std. Dev.)	(Std. Dev.)	(Std. Dev.)	(Std. Dev.)	(Std. Dev.)	(Std. Dev.)	(Std. Dev.)	(Std. Dev.)
0	33.5 (0.38)	0.21 (0.0005)	33.5 (0.38)	0.21 (0.0005)	33.5 (0.38)	0.21 (0.0005)	33.5 (0.38)	0.21 (0.0005)
5	20.3 (0.37)	0.20 (0.0006)	19.7 (0.38)	0.20 (0.0005)	22.2 (0.39)	0.20 (0.0007)	23.5 (0.37)	0.20 (0.0006)
10	16.1 (0.46)	0.14 (0.0008)	20.3 (0.4)	0.18 (0.0007)	17.9 (0.38)	0.19 (0.0006)	20.2 (0.39)	0.17 (0.0005)
15	18.3 (0.42)	0.17 (0.0007)	16.8 (0.41)	0.16 (0.0005)	19.2 (0.4)	0.21 (0.0006)	19.3 (0.39)	0.22 (0.0005)
20	18.4 (0.39)	0.19 (0.0006)	13.6 (0.38)	0.16 (0.0007)	18.4 (0.39)	0.19 (0.0007)	18.5 (0.4)	0.20 (0.0008)

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Fig1a-FBA 1

Fig1b-FBA 2

Fig1c-FBA 3

Fig1d-FBA 4

475 Figure 1- X-Ray Diffractograms on Forest Based Ash Samples

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Fig 2a-FBA 1

Fig 2b-FBA 2

Fig 2c-FBA 3

Fig 2d-FBA 4

Figure 2- Scanning Electron Micrographs of FBA Samples

Figure 3- Particle Size Distribution Curves of OPC and FBA

Fig 4a-CFBA 1

Fig 4b-CFBA 2

Fig 4c-CFBA 3

Fig 4d-CFBA 4

Figure 4- Development of Compressive Strength over 28 days in Mixtures Containing a) FBA 1; b) FBA 2; c) FBA 3 and d) FBA 4

Figure 5- Variation of 28 Days Compressive Strength of Concretes with Different Ash Samples

Fig 6a- CFBA 1

Fig 6b- CFBA 2

Fig 6c- CFBA 3

Fig 6d- CFBA 4

Figure 6- Development of Tensile Strength over 28 days in Mixtures Containing a) FBA 1; b) FBA 2; c) FBA 3 and d) FBA 4

Figure 7- Variation of 28 Days Tensile Strength of Concretes with Different Ash Samples

Figure 8- Modulus of Elasticity of Concrete Mixtures with Different Percentages of FBAs