# Center for By-Products Utilization

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**Synopsis:** This investigation was carried out to establish production of concrete mixtures incorporating wood fly ash (FA). Two series of non-air entrained concrete mixtures were developed for this project using two different sources of wood FA and two different sources of ASTM C 618 Class C coal FA. Each series of concrete mixtures consisted of eight different mixture proportions including a reference mixture without any wood FA or coal FA. Three of these mixtures were developed to have wood FA contents of approximately 15%, 25%, and 35% as a partial replacement of cement. Four additional mixtures were developed using blends of wood FA and Class C coal FA. Two levels of blended ash of approximately 25% and 35% were used. The effect of source of wood FA was noticeably different on the performance of concrete. Blending of wood FA with Class C coal FA improved performance of wood FA to a significant extent. The results revealed that structural-grade concrete can be made using wood FA and/or its blends with Class C coal FA as a replacement of cement. Compressive strength values of up to 40 to 50 MPa (6,000 to 7,500 psi) at 28-day to 91-day ages were achieved.

**Keywords:** Coal Fly Ash, Compressive Strength, Concrete, Drying Shrinkage, Tensile Strength, Wood Fly Ash.

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## INTRODUCTION

Wood FA is generated due to combustion of wood for energy production at pulp and paper mills, saw mills, and wood-products manufacturing facilities. Typically, wood burned for fuel at pulp and paper mills and the wood- products industry may consist of saw dust, wood chips, bark, saw mill scraps, hard chips rejected from pulping, excess screenings such as sheaves, primary residuals without mixed secondary residuals, etc. Physical and chemical properties of wood FA are of special importance in determining their beneficial uses. These properties are influenced by species of trees, tree growing regions and conditions, method and manner of combustion including combustion temperature, other supplementary fuel used with wood fuel, and method of wood FA collection [1, 2, 3]. Wood is often co-fired with supplementary fuels such as coal, coke, oil, gas, etc. Approximately 70% of the wood FA generated in the U.S.A. is landfilled; and approximately 25% is applied on land as a soil supplement [4-12]. The remaining 5% has been used for miscellaneous applications [1-4] including construction materials, metal recovery, and pollution control. Landfilling is becoming very restrictive due to shrinking landfill space and strict environmental regulations. The use of wood FA as a soil supplement is also becoming more limited due to the presence of some heavy metals, as well as reduced availability of land for application. Due to these reasons, attempts have recently been made to develop high-volume use technologies for wood FA, especially for use as construction materials [8,13]. Due to the high carbon content in wood FA, use may be limited to low- and medium-strength and/or non-air entrained concrete. Naik [8] reported that wood FA has a substantial potential for use as a pozzolanic mineral admixture and as an activator in cement-based materials.

Prior to the use of wood FA in cement-based materials, laboratory evaluation is necessary to develop mixture proportions and production technology for concrete using wood FA for various applications. The investigation reported in this paper was undertaken to develop concrete mixtures incorporating wood FA derived from two different sources.

## EXPERIMENTAL PROGRAM

Materials utilized for this project consisted of wood FA, cement, fine aggregate, coarse aggregate, and coal FA. All test materials were characterized for physical and chemical properties in accordance with the appropriate ASTM or other applicable standards.

Two different sources of wood FA designated as W-1 and W-2 were utilized in this work. These wood fly ashes were tested for various properties in accordance with requirements of ASTM C 618 (Tables 1 and 2). Wood FA W-1 did not meet the ASTM C 618 requirements for water requirement and loss on ignition (LOI), while wood FA W-2 did not meet the requirements for Strength Activity Index with cement, water requirement, total $SiO_2$ + $Al_2O_3$ + $Fe_2O_3$, and LOI. Fine aggregate and coarse aggregate conforming to ASTM C 33 requirements were used in this investigation. Two sources of coal FA conforming to ASTM C 618 Class C fly ash were used (Tables 1 and 2). One source of Type I cement meeting ASTM C 150 requirements was used throughout this investigation.

## Mixture Proportions

Two control mixtures, one for each series of concrete mixtures, were proportioned without wood FA or Class C FA (Tables 3 and 4). Each Series of concrete mixtures consisted of seven additional concrete mixtures. Of these, three mixtures were developed to have wood FA contents of approximately 15%, 25%, and 35% as replacement of cement using a ratio of cement replaced to fly ash inclusion of 1.25 on a mass basis. Four additional mixtures were developed using blends of wood FA and ASTM Class C coal FA. Two levels of blended ash of approximately 25% and 35% by mass of total cementitious materials were used. The blended ash samples were prepared using equal amounts of wood FA and Class C coal FA. The slump of all concrete mixtures was maintained at about 100 ± 25 mm (4. ± 1 in.). The amount of water added to the concrete mixtures was varied to achieve the desired level of slump.

## Manufacturing of Concrete Mixtures

Concrete ingredients were manually weighed and loaded in a rotating drum concrete mixer. All concrete mixtures were made in accordance with ASTM C 192. Before discharging the concrete mixture, slump (ASTM C 143) of the mixture was measured and additional water was added as required to achieve the desired slump of approximately 100 mm (4 in.). Whenever additional water was added to obtain the specified fresh concrete characteristics, the concrete mixture was mixed for an additional three minutes. The concrete was then placed onto a moistened pan for further testing and evaluation.

## Specimen Preparation And Testing

Fresh concrete properties including slump (ASTM C 143), air content (ASTM C 138), unit weight (ASTM C 138), and concrete temperature (ASTM C 1064) were measured for each mixture. Ambient air temperature was also measured and recorded. For each concrete mixture, test specimens were cast in the laboratory in accordance with ASTM C 192. Test specimens of 100x200-mm (4x8-in. cylinders) were cast for compressive strength (ASTM C 39) and splitting tensile strength (ASTM C 78) measurements.

## RESULTS AND DISCUSSION

### Fresh Concrete Properties

Mixture proportions and fresh properties of the concrete mixtures are shown in Tables 3 and 4. The slump was varied between 88 and 112 mm (3 ½ and 4 ½ in.) for the W-1 mixtures, and 95 and 112 mm (3 ¾ and 4 ½ in.) for the W-2 mixtures. In general, unit weight of the mixtures decreased with increasing wood FA content, especially for high-LOI wood FA W-2. Test results show that the unit weight of the concrete mixtures depended upon the source of wood FA. The unit weight of the Wood FA W-1 concrete mixtures (2,339-2,371 kg/m$^3$, 146-148 lb/ft$^3$) was higher than the W-2 concrete mixtures (2,243-2,323 kg/m$^3$, 140-145 lb/ft$^3$). This was primarily due to the high LOI of the wood FA W-2 compared to wood FA W-1. To maintain the target slump level for the wood FA W-2 mixture, the water to cementitious materials ratio also increased from 0.51 to 0.69 as the amount of wood FA W-2 was increased, due to the increased amount of water demand for high LOI wood FA W-2.

### Hardened Concrete

**Compressive Strength --** The compressive strengths of the concrete mixtures as a function of age are presented in Fig. 1 for the wood FA W-1 mixtures and Fig. 2 for the wood FA W-2 mixtures. The control mixtures (C-1 and C-2) achieved a compressive strength of over 20 MPa (3,000 psi) at the age of 3 days, over 35 MPa (5,000 psi) at the age of 28 days, and over 40 MPa (5,800 psi) at the age of 91 days. The control mixtures were proportioned for compressive strengths greater than 35 MPa (5,000 psi) at the age of 28days. The compressive strengths of the concrete mixtures containing wood FA W-1 are shown in Fig. 1. The compressive strengths of the concrete mixtures containing wood FA W-1 without coal FA ranged from 14.8 to 22.1 MPa (2,140 psi to 3,200 psi) at the age of three days, 29.6 to 41.4 MPa (4,290 psi to over 6,000 psi) at 28 days, and 34.7 to 54.0 MPa (5,030 psi to over 7,830 psi) at the age of 91 days. The compressive strength of the mixture containing 14% wood FA W-1 (Mixture 1-1), and the Mixture 1C2-1 (blend of 12% wood FA W-1 and 12% Class C FA C2) exceeded the compressive strength of the control mixture at all test ages. The compressive strengths of Mixtures 1-2 (25% wood FA W-1), 1C1-1 (blend of 12% wood FA W-1 and Class C FA C1), 1C1-2 (blend of 17% wood FA W-1 and 17% Class C FA C1), and 1C2-2 (blend of 17% wood FA W-1 and 17% Class C FA C2) were lower compared to the control mixture. However, at later ages of 28 days and beyond, the compressive strengths of these mixtures exceeded the control mixture. Generally, Mixture 1-3 (35% wood FA W-1) exhibited lower compressive strengths relative to the control mixture at all ages. However, the compressive strength of this mixture exceeded 29 MPa (4200 psi) at 28 days and beyond.

The compressive strengths of the concrete mixtures incorporating wood FA W-2 without coal FA varied from 8.7 to 15.9 MPa (1,260 to 2,300 psi) at 3 days, 9.3 to 32.4 MPa (1,355 to 4,695 psi) at 28 days, and 12.1 to 39.1 MPa (1,750 to 5,670 psi) at 91 days. Mixture 2-1 (14% wood FA W-2) achieved a compressive strength of 25.6 MPa (3,710 psi) at the age of 28 days. Mixtures 2-2 and 2-3 (24% and 35% wood FA W-2) did not achieve a minimum design compressive strength of 20.7 MPa (3,000 psi) at the age of 28 days. However, the performance of the concrete mixtures significantly improved when blends of wood FA W-2 and Class C FA were used. This was especially true for the mixtures that contained 12% of wood FA W-2 and Class C FA (Mixtures 2C1-1 and 2C2-1). The concrete with wood FA W-2 also performed better when combined with Class C FA C1 rather than C2 Class C FA. The 35% wood FA W-2 with Class C FA C1 blend achieved a compressive strength of 24.7 MPa (3,580 psi) at 28 days of age. However, the 35% blend with coal ash C2 just failed to meet the 20.7 MPa (3,000 psi) strength at the age of 28 days.

The above results show that the performance of wood FA W-1 in concrete is better than wood FA W-2. This was attributed to the better reactivity of wood FA W-1 due to its favorable physical and chemical properties compared to wood ash W-2, and especially very high LOI of wood FA W-2. In general, blending wood FA with Class C FA resulted in improved performance of concrete especially coal FA C1. This was due to better physical and chemical properties of Class C FA relative to wood FA, which resulted in improved wood FA when blended with Class C FA.

**Tensile Strength --** The splitting tensile strength data are presented in Figs. 3 and 4. The control mixtures (C-1 and C-2) achieved tensile strengths in the range of 2.5 to 2.9 MPa (360 to 420 psi) at the age of 3 days, 3.9 to 4.3 MPa (565 to 620 psi) at the age of 28 days, and 3.9 to 4.3 MPa (565 to 620 psi) at the age of 91 days. The splitting tensile strength of the concrete mixtures containing wood FA generally followed the same general pattern as was described previously for the compressive strength data. The tensile strength of the concrete mixtures made with wood FA W-1 is compared to the strength of the Control mixture C-2. The tensile strengths of the concrete mixtures containing wood FA W-1 without coal fly ash were 2.1 to 2.9 MPa (300 to 415 psi) at three days, 3.2 to 3.9 MPa (460 to 565 psi) at 28 days, and 4.0 to 5.0 MPa (580 to 720 psi) at the age of 91 days. The tensile strength values of Control Mixture C-2 were 2.5 MPa (360 psi) at 3 days, 3.9 MPa (565 psi) at 28 days, and 4.7 MPa (685 psi) at 91 days. The tensile strength of Mixtures 1-1 (14% wood FA W-1), 1C1-1 (blend of 12% wood FA W-1 and 12% Class C FA C1), 1C1-2 (blend of 17% wood FA W-1 and 17% Class C FA C1), and 1C2-2 (blend of 17% wood FA W-1 and 17% Class C FA C2), were equivalent or better than the control mixture at the age of 91 days. All other concrete mixtures developed sufficient strength for most structural applications. The tensile strengths of concrete mixtures containing wood FA W-2 were compared to Control Mixture C-2, Fig. 4. The tensile strengths of the mixtures containing wood FA without coal FA W-2 were 1.0 to 2.0 MPa (140 to 285 psi) at three days, 1.6 to 3.3 MPa (235 to 480 psi) at 28 days, and 2.0 to 3.8 MPa (285 to 555 psi) at the age of 91 days. The tensile strengths of the mixtures made with blends of wood FA W-2 and coal FA were 1.3 to 2.3 MPa (195 to 340 psi) at three days, 2.8 to 3.4 MPa (410 to 500 psi) at 28 days, and 3.6 to 4.3 MPa (525 to 625 psi) at 91 days. Although these mixtures had generally lower tensile strengths than the Control Mixture, they all achieved sufficient tensile strength for most structural applications.

## CONCLUSIONS

1. Physical and chemical properties of wood fly ashes were significantly influenced by the source of wood FA, especially fineness, strength activity with cement, and LOI.
2. Although wood ashes did not conform to ASTM C 618 requirements for coal fly ash, they were found to be suitable for use in producing structural-grade concrete.
3. Pozzolanic contributions of wood ashes were found to be significant. However, it was less than that of ASTM Class C FA used in this project. Blending of wood FA with Class C FA resulted in significant improvement in performance of concrete.
4. Generally, concrete compressive and splitting tensile strengths decreased as the amounts of wood FA increased.
5. Concrete mixtures containing a blend of wood FA and ASTM C 618 Class C fly ash achieved higher compressive and tensile strengths than comparable mixtures only containing wood FA.
6. Non-air entrained concrete mixtures with wood FA W-1 can be proportioned to meet strength requirements for structural applications. However, the mixtures made with wood FA W-2 may be used in other concrete construction work.
7. Drying shrinkage of the concrete mixtures containing wood FA W-2 was lower than that for the wood FA W-1 concrete mixtures. Due to high shrinkage of wood ash W-1 concrete, wood FA W-1 should be further evaluated before recommending its use in actual construction applications.

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Table 1 - Physical Properties of Wood Fly Ash and Class C Fly Ash

| TEST PARAMETER | Ash Source Number | | | | ASTM C 618 Specifications | |
|---|---|---|---|---|---|---|
| | W-1 | W-2 | C1 | C2 | CLASS C | CLASS F |
| Retained on No.325 sieve (%) | 23 | 60 | 10 | 12 | 34 max | 34 max |
| Strength Activity Index with Cement (% of Control) | | | | | | |
| 3-day | 88.4 | 38.4 | 109.2 | 99.1 | | |
| 7-day | 84.2 | 39.4 | 110.8 | 109.5 | 75 min | 75 min |
| 28-day | 88.3 | 33.6 | 104.7 | 93.1 | 75 min | 75 min |
| Water Requirement (% of Control) | 115 | 155 | 95 | 100 | 105 max | 105 max |
| Autoclave Expansion (%) | 0.2 | 0.5 | 0.08 | -0.09 | ±0.8 | ±0.8 |
| Unit Weight, $kg/m^3$ ($lb/ft^3$) | 545 (34.0) | 412 (25.7) | 1083 (67.6) | 1310 (81.8) | - | - |
| Specific Gravity | 2.26 | 2.41 | 2.58 | 2.62 | - | - |

Table 2 - Analysis for Oxides, $SO_3$, and Loss on Ignition for Wood and Class C Fly Ashes

| Analysis Parameter | Ash Source Number | | | | ASTM C 618 Requirements | | |
|---|---|---|---|---|---|---|---|
| | W-1 | W-2 | C1 | C2 | Class C | Class F | Class N |
| Silicon Dioxide, $SiO_2$ | 32.4 | 13.0 | 36.6 | 36.9 | -- | -- | -- |
| Aluminum Oxide, $Al_2O_3$ | 17.1 | 7.8 | 19.5 | 19.5 | -- | -- | -- |
| Iron Oxide, $Fe_2O_3$ | 9.8 | 2.6 | 5.9 | 5.5 | -- | -- | -- |
| $SiO_2$ + $Al_2O_3$ + $Fe_2O_3$ | 59.3 | 23.4 | 61.0 | 61.9 | 50 min | 70 min | 70 min |
| Calcium Oxide, CaO | 3.5 | 13.7 | 26.1 | 26.7 | -- | -- | -- |
| Magnesium Oxide, MgO | 0.7 | 2.6 | 6.4 | 5.4 | -- | -- | -- |
| Titanium Oxide, $TiO_2$ | 0.7 | 0.5 | 1.4 | 1.4 | -- | -- | -- |
| Potassium Oxide, $K_2O$ | 1.1 | 0.4 | 0.5 | 0.5 | -- | -- | -- |
| Sodium Oxide, $Na_2O$ | 0.9 | 0.6 | 2.2 | 2.1 | -- | -- | -- |
| Sulfur Trioxide, $SO_3$ | 2.2 | 0.9 | 1.2 | 1.5 | 5 max | 5 max | 4 max |
| Loss on Ignition, LOI ($1000^0$C) | 31.6 | 58.1 | 0.4 | 0.3 | 6 max | 6 max | 10 max |
| Moisture | 2.4 | 0.5 | 0.2 | 0.1 | 3.0 max | 3.0 max | 3.0 max |
| Available Alkali, Equ. $Na_2O$, (ASTM C-311) | 0.9 | 0.4 | N.A. | N.A. | 1.5 max | 1.5 max | 1.5 max |

Table 3 - Non Air-Entrained Concrete Mixture Proportions – Wood Ash Source W-1

| Mixture No. | C-2 | 1-1 | 1-2 | 1-3 | 1C1-1 | 1C2-1 | 1C1-2 | 1C2-2 |
|---|---|---|---|---|---|---|---|---|
| Wood FA | -- | W-1 | W-1 | W-1 | W-1 | W-1 | W-1 | W-1 |
| Class C FA | -- | -- | -- | -- | C1 | C2 | C1 | C2 |
| Fly Ash, %* | 0 | 14 | 25 | 35 | 25 | 25 | 34 | 35 |
| Cement, C, kg/m$^3$ (lb/yd$^3$) | 347 (585) | 303 (510) | 273 (460) | 231 (390) | 273 (460) | 273 (460) | 237 (400) | 234 (395) |
| Wood FA, kg/m$^3$ (lb/yd$^3$), A1 | 0 | 50 (85) | 89 (150) | 125 (210) | 45 (75) | 45 (75) | 62 (105) | 62 (105) |
| Class C FA, kg/m$^3$ (lb/yd$^3$), A2 | 0 | 0 | 0 | 0 | 45 (75) | 45 (75) | 62 (105) | 62 (105) |
| Water, W, kg/m$^3$ (lb/yd$^3$) | 166 (280) | 193 (325) | 196 (330) | 187 (315) | 172 (290) | 166 (280) | 172 (290) | 172 (290) |
| [W/(C+A)] | 0.48 | 0.55 | 0.55 | 0.53 | 0.47 | 0.46 | 0.48 | 0.48 |
| SSD Fine Agg., kg/m$^3$ (lb/yd$^3$) | 795 (1340) | 819 (1380) | 819 (1380) | 798 (1345) | 819 (1380) | 825 (1390) | 813 (1370) | 810 (1365) |
| SSD Coarse Agg., kg/m$^3$ (lb/yd$^3$) | 1086 (1830) | 991 (1670) | 997 (1680) | 985 (1660) | 1000 (1685) | 1009 (1700) | 1003 (1690) | 1000 (1685) |
| Slump, mm (in) | 102 (4) | 83 (3 ¼) | 102 (4) | 89 (3 ½) | 89 (3 ½) | 89 (3 ½) | 89 (3 ½) | 102 (4) |
| Air Content (%) | 1.1 | 1.1 | 1.4 | 1.4 | 1.1 | 1.5 | 1.8 | 1.1 |
| Air Temp., °C ($^0$F) | 27.8 (82) | 25.6 (78) | 24.4 (76) | 26.7 (80) | 25.6 (78) | 26.7 (80) | 26.7 (80) | 26.7 (80) |
| Concrete Temp., °C ($^0$F) | 28.3 (83) | 27.8 (82) | 25.8 (77) | 25.6 (78) | 25.6 (78) | 27.8 (82) | 27.2 (81) | 28.9 (84) |
| Fresh Conc. Density, kg/m$^3$ (lb/ft$^3$) | 2390 (149.2) | 2371 (148) | 2355 (147) | 2275 (142) | 2355 (147) | 2371 (148) | 2355 (147) | 2339 (146) |

*Fly ash as a percentage of total cementitious materials, (A1+A2)/ (Cement +A1+A2)
**A=A1+A2

Table 4 - Non Air-Entrained Concrete Mixture Proportions - Wood Ash Source W-2

| Mixture No. | C-1 | 2-1 | 2-2 | 2-3 | 2C1-1 | 2C2-1 | 2C1-2 | 2-C2-2 |
|---|---|---|---|---|---|---|---|---|
| Wood FA | -- | W-2 | W-2 | W-2 | W-2 | W-2 | W-2 | W-2 |
| Class C FA | -- | -- | -- | -- | C-1 | C-2 | C-1 | C-2 |
| FA, % | 0 | 14 | 24 | 35 | 24 | 24 | 36 | 36 |
| Cement, C, kg/m$^3$ (lb/yd$^3$) | 329 (555) | 303 (510) | 255 (430) | 202 (340) | 261 (440) | 261 (440) | 234 (395) | 208 (350) |
| Wood FA, kg/m$^3$ (lb/yd$^3$), A1 | 0 | 50 (85) | 80 (135) | 110 (185) | 42 (70) | 42 (70) | 65 (110) | 59 (100) |
| Class C FA, kg/m$^3$ (lb/yd$^3$), A2 | 0 | 0 | 0 | 0 | 42 (70) | 42 (70) | 65 (110) | 59 (100) |
| Water, W, kg/m$^3$ (lb/yd$^3$) | 169 (285) | 187 (315) | 199 (335) | 217 (365) | 184 (310) | 187 (315) | 187 (315) | 184 (310) |
| [W/(C+A)]** | 0.51 | 0.53 | 0.59 | 0.69 | 0.53 | 0.54 | 0.51 | 0.56 |
| SSD Fine Agg., kg/m$^3$ (lb/yd$^3$) | 813 (1370) | 786 (1325) | 708 (1195) | 626 (1055) | 733 (1235) | 733 (1235) | 730 (1230) | 650 (1095) |
| SSD Coarse Agg., kg/m$^3$ (lb/yd$^3$) | 1083 (1825) | 1006 (1695) | 1029 (1735) | 1050 (1770) | 1050 (1770) | 1050 (1770) | 1219 (2055) | 1089 (1835) |
| Slump, mm (in) | 76 (3) | 102 (4) | 114 (4 ½ ) | 102 (4) | 102 (4) | 102 (4) | 95 (3 ¾ ) | 102 (4) |
| Air Content (%) | 1.1 | 1.2 | 1.8 | 2.2 | 1.7 | 1.8 | 2 | 1.9 |
| Air Temp., $^0$C ($^0$F) | 27.8 (82) | 27.2 (81) | 28.3 (83) | 25.6 (78) | 26.6 (80) | 25.0. (77) | 26.6 (80) | 28.8 (84) |
| Con. Temp., $^0$C ($^0$F) | 28.3 (83) | 26.6 (80) | 28.3 (83) | 26.6 (80) | 27.2 (81) | 26.6 (80) | 27.8 (82) | 26.6 (80) |
| Fresh Conc. Density, kg/m$^3$ (lb/ft$^3$) | 2397 (149.6) | 2307 (144) | 2275 (142) | 2227 (139) | 2323 (145) | 2307 (144) | 2307 (144) | 2243 (140) |

*Fly ash as a percentage of total cementitious materials, (A1+A2)/ (Cement +A1+A2)
**A=A1+A2

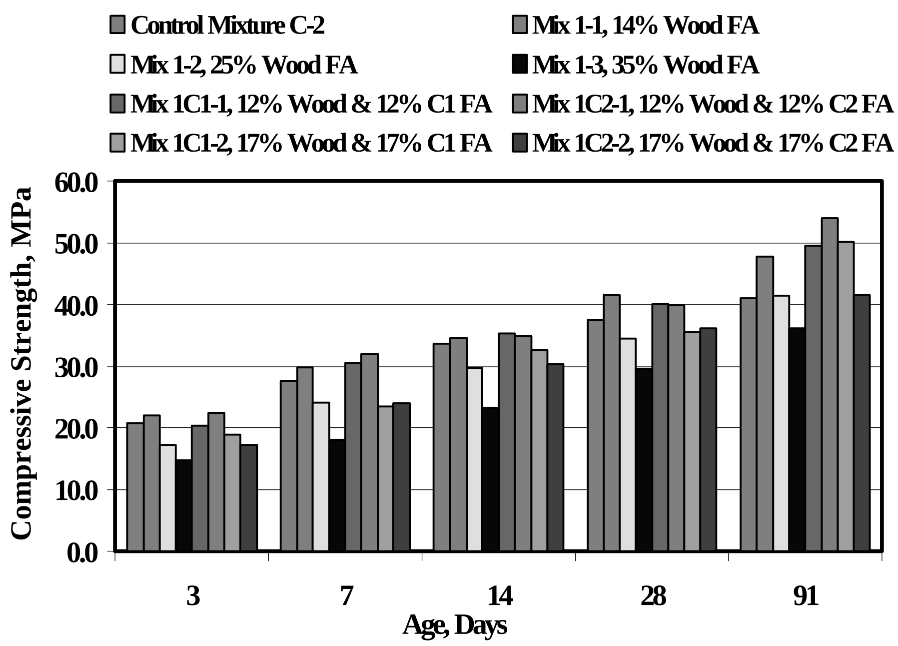



Fig. 1 - Compressive Strength of the Wood Ash Source W-1 Concrete Mixtures

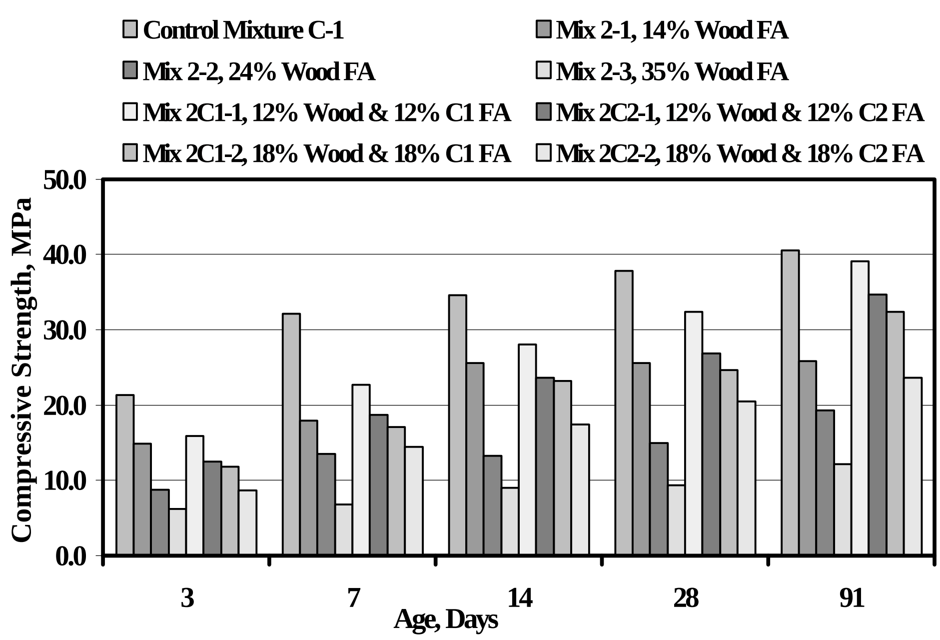
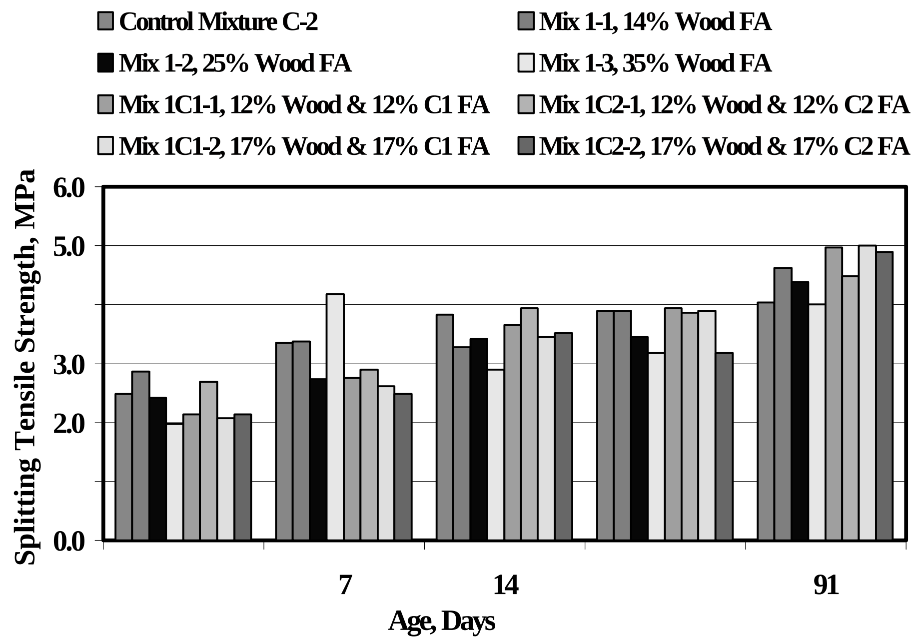



Fig. 2 - Compressive Strength of the Wood Ash Source W-2 Concrete Mixtures




Concrete Mixtures

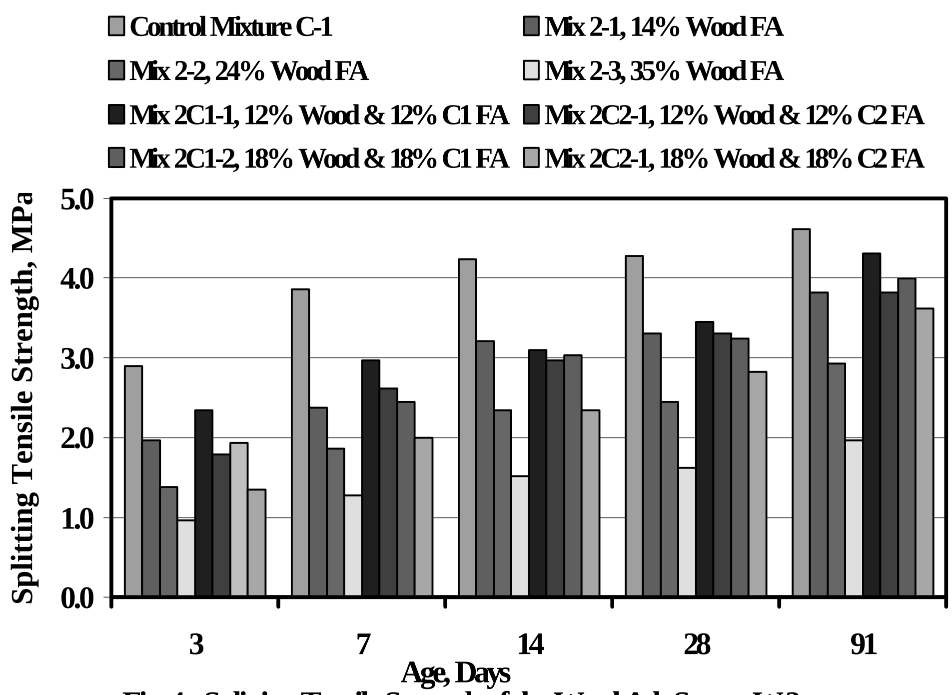



Fig. 4 - Splitting Tensile Strength of the Wood Ash Source W-2 Concrete Mixtures