# Pulp and paper mill fibrous residuals in excavatable flowable fill

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ABSTRACT: This research was conducted to develop flowable slurry containing fibrous residuals from pulp and paper mills. Two types of flowable slurry containing ASTM Class C fly ash were produced: fly ash slurry and sandy slurry. Often, the fly ash slurry made without fibrous residuals showed a tendency to set rapidly, and become unworkable. When the cement-to-fly ash ratio was increased to extend the time of setting, the long-term strength of the hardened slurry often became too high (unexcavatable). The problem of excessively high long-term strength was also sometimes observed in the case of sandy slurry made without fibrous residuals. In comparison, by using the fibrous residuals (and without using a chemical retarder): (a) fly ash slurry maintained workability (no rapid setting) and desirably low long-term strength, allowing for excavation; and (b) sandy slurry maintained low long-term strength. Thus, this research showed that the fibrous residuals from pulp and paper mills are useful in controlling the setting behavior and long-term strength of flowable slurry containing fly ash.

## 1 INTRODUCTION

This research was conducted to develop flowable slurry containing fibrous residuals from the pulp and paper industry.

### 1.1 *Fibrous residuals from pulp and paper mills*

Fibrous residuals from pulp and paper mills include wastewater-treatment residuals (also called sludge), fiber reclaim, and screening rejects. The basic components of the wastewater-treatment residuals are wood cellulose fibers and moisture. Wastewater-treatment residuals from a number of mills also contain papermaking fillers (kaolinitic clay, calcium carbonate, and/or titanium dioxide) and the biomass from biological treatment of wastewater. Fiber reclaim is composed of wood cellulose fibers and moisture. Screening rejects are made up of moisture and the shives (coarse bundles of wood fibers) and wood pieces that are unsuitable for pulp and paper manufacturing.

In 1995, the U.S. pulp and paper industry generated about 5.3 million tonnes (on an oven-dry basis) of mill wastewater-treatment residuals, which is equivalent to about 15 million tonnes of dewatered moist residuals [NCASI 1999]. About half of this was disposed in landfills/lagoons, 1/4 was burned (typically no energy benefit), 1/8 was applied on farmland/forest, 1/16 was reused/recycled in mills, and the final 1/16 was used in other ways. Due to the increasing cost of landfilling, increasingly stringent environmental regulations, and potential long-term environmental liabilities, the percentage of the residuals disposed in landfills has decreased considerably over the past several decades (from 86% in 1979 to 70% in 1988, and to 51% in 1995) [NCASI 1992, Unwin 2000, NCASI 1999]. A significant amount of residuals, however, still needs to be diverted from landfilling.

### 1.2 *Controlled low-strength materials*

Controlled low-strength material (CLSM) is a cementitious material that is in a flowable state at the time of placement and has a specified compressive strength of 8.3 MPa (1200 psi) or less [ACI 1999]. CLSM is also called flowable fill or flowable slurry. CLSM is used primarily for non-structural and light-structural applications such as backfills, conduit bedding, erosion control, void filling, heat-insulation fills, sound-isolating fills, and pavement bases. CLSM is mainly used as a self-leveling/self-consolidating slurry material for backfilling of trenches, bridge abutments, and other cavities. It is generally required to have a low long-term strength to allow for future excavation. CLSM with relatively high strength can be used in applications where future excavation is unlikely, such as structural fill under buildings. In deciding mixture proportions of CLSM, factors such as flowability, strength, and excavatability are evaluated. For many uses, permeability is also an important property of CLSM. Permeability of CLSM depends on properties of constituent materials, mixture proportions including water-cementitious materials ratio (W/Cm), and age. Conventionally, there are two types of CLSM: (1) fly ash CLSM made with water, very little cement, and a lot of fly ash; and (2) sandy CLSM made with water, a lot of sand, very little cement, and some fly ash.

### 1.3 *Use of the fibrous residuals in cement-based materials*

Recent research projects have shown that fibrous residuals from pulp and paper mills improve the durability of concrete [Naik et al. 2005]. The fibrous residuals increased the resistance of non-air-entrained concrete to freezing-and-thawing and to salt scaling.

The use of the fibrous residuals in cement-based materials could become an economical alternative to landfilling, burning, or other management options. This research was conducted to develop mixture proportions of CLSM containing the fibrous residuals from pulp and paper mills and to evaluate the technical benefits of using the fibrous residuals in CLSM.

## 2 MATERIALS

### 2.1 *Cement, sand, and fly Ash*

ASTM Type I portland cement and natural sand were used. The chemical composition of the cement was 20.2% $SiO_2$, 4.5% $Al_2O_3$, 2.6% $Fe_2O_3$, 64.2% CaO, 2.5% MgO, 2.4% $SO_3$, 0.53% total alkalies as $Na_2O$, 1.4% loss on ignition, 0.4% insoluble residue, and 1.5% free lime. ASTM Class C fly ash was obtained from Green Bay, Wisconsin, USA. The strength activity index of fly ash (measured by testing mortar containing fly ash as a replacement of 20% of cement) was 98% and 99% of Control (0% fly ash) at 7 and 28 days, respectively. Water requirement of the mortar containing fly ash was 91% of Control. Density of fly ash was 2.86 g/cm$^3$. The oxides composition of fly ash was 39.1% $SiO_2$, 18.6% $Al_2O_3$, 5.6% $Fe_2O_3$, 21.3% CaO, 5.0% MgO, 1.6% $SO_3$, 1.7% $Na_2O$, and 0.8% $K_2O$.

### 2.2 *Fibrous residuals*

Fibrous residuals were obtained from two sources: (1) WR, screening rejects from a pulp mill in Rothchild, Wisconsin; and, (2) C1, wastewater-treatment residual from pulp and paper mills in Stevens Point, Wisconsin.

Since Residual C1 was known to mildew and decompose in a warm and humid environment, it was stored in a walk-in refrigerator maintained at approximately 4°C. Residual WR was also stored in the refrigerator, although it does not decompose even at room temperature.

Table 1 presents the type and description of the fibrous residuals. Table 2 presents the properties of the fibrous residuals.

Table 1. Type and description of residual solids.

| Fibrous residual | Type | Fiber source | Source mill type | Appearance |
|---|---|---|---|---|
| WR | Screening rejects | Virgin | Pulp | Brown shives and wood pieces |
| C1 | Waste-water treatment residual | Virgin | Pulp and paper | Light gray, and clayey |

Table 2. Properties of fibrous residuals.

| Fibrous residual | Moisture content (%) | Apparent specific gravity* | Average length of fibers†, $L_L$ (mm) | Average width of fibers (mm) |
|---|---|---|---|---|
| WR | 200 | 1.45 | 0.68 | 0.031 |
| C1 | 141 | 1.75 | 0.61 | 0.021 |

* Specific gravity tests were performed on as-received moist samples of fibrous residuals.

† Length-weighted average length, $L_L = \sum_{i=1}^{N} n_i l_i^2 \Big/ \sum_{i=1}^{N} n_i l_i$ .

Note: The length and width of the wood fibers in the fibrous residuals were determined using the Techpap MorFi LB01 system.

## 3 MIXTURE PROPORTIONS, TEST RESULTS, AND DISCUSSION

### 3.1 *Mixture proportions*

The fibrous residuals were used as-received and not "repulped." Mixture proportions were established through preliminary mixing and testing of ash and sandy flowable slurry mixtures containing various amounts of cement, fly ash, water, and fibrous residuals. Mixture proportions and fresh properties of final ash and sandy slurry mixtures are shown in Table 3 and Table 4.

The ash slurry mixtures containing fibrous residuals were made with lower amounts of cementitious materials (cement plus fly ash) than the ash slurry mixtures FA-Ref and FA-Ref-2 containing no fibrous residuals (Table 3). This was mainly because fibrous residuals are bulky in comparison with cement and fly ash. The water-cementitious materials ratio (W/Cm) of Mixtures FA-Ref and FA-Ref-2 was lower than the ash slurry mixtures containing fibrous residuals. In addition, the cement-cementitious materials ratio (C/Cm) of Mixtures FA-Ref and FA-Ref-2 was higher than the ash slurry mixtures containing fibrous residuals. This was done in an effort to avoid rapid setting of the ash slurry made with Class C fly ash and without fibrous residuals.

The fly ash slurry mixtures FA-Ref and FA-Ref-2 containing no fibrous residuals were very cohesive in the mixer-drum and scoops, and not easy to handle. On the other hand, the fly ash slurries containing fibrous residuals were easy to produce and handle. Mixtures FA-Ref and FA-Ref-2 showed generally higher flow than the ash slurry mixtures containing fibrous residuals.

In spite of the relatively high C/Cm, the ash slurry mixture FA-Ref set and hardened soon after specimens were cast, in about 30 minutes after mixing started, due to a high amount of Class C fly ash. The ash slurry mixture FA-Ref-2 was made with a higher C/Cm to avoid the rapid setting and hardening. In comparison, the fly ash slurry mixtures containing fibrous residuals remained workable while specimens were being cast.

Sandy slurry mixtures Sd-Ref and Sd-Ref-2 were produced with relatively low amounts of cementitious materials to limit their long-term compressive strength (Table 4). The sandy slurry mixtures containing fibrous residuals were produced with twice as much cementitious materials to avoid excessive delay in setting; a high long-term strength was not a concern. It was easy to produce and handle sandy slurry mixtures, regardless of whether fibrous residuals were used or not.

Table 3. Mixture proportions and fresh properties of fly ash flowable slurry.

| Mixture designation | FA-Ref | FA-Ref-2 | FA-WR | FA-WR-2 | FA-C1 | FA-C1-2 |
|---|---|---|---|---|---|---|
| Fibrous residual | (None) | (None) | WR | WR | C1 | C1 |
| Cement (kg/m$^3$), C | 75 | 179 | 25 | 27 | 21 | 29 |
| Class C fly ash (kg/m$^3$), FA | 1213 | 1612 | 811 | 877 | 692 | 923 |
| Cementitious materials* (kg/m$^3$), Cm | 1288 | 1791 | 837 | 905 | 713 | 952 |
| Sand, SSD (kg/m$^3$), Sd | 0 | 0 | 0 | 0 | 0 | 0 |
| Fibrous residual (kg/m$^3$), R | 0 | 0 | 167 | 181 | 285 | 190 |
| Water (kg/m$^3$), W | 496 | 645 | 522 | 456 | 445 | 444 |
| C/Cm | 0.06 | 0.10 | 0.03 | 0.03 | 0.03 | 0.03 |
| FA/Cm | 0.94 | 0.90 | 0.97 | 0.97 | 0.97 | 0.97 |
| R/Cm | 0 | 0 | 0.20 | 0.20 | 0.40 | 0.20 |
| Sd/Cm | 0 | 0 | 0 | 0 | 0 | 0 |
| W/Cm | 0.39 | 0.36 | 0.62 | 0.50 | 0.62 | 0.47 |
| R/Slurry | 0 | 0 | 0.11 | 0.12 | 0.20 | 0.12 |
| Flow, 75 × 150 mm cylinder (mm) | 335 | 415 | 380 | 230 | 235 | 275 |
| Air content (%) | 0.8 | 1.2 | n. a. | 3.1 | 3.0 | 1.8 |
| Air temperature (°C) | 20 | 20 | 20 | 20 | 20 | 20 |
| Slurry temperature (°C) | 29 | 23 | n. a. | 19 | 20 | 22 |
| Density (kg/m$^3$) | 1780 | 2440 | 1530 | 1540 | 1440 | 1590 |

* Cement plus Class C fly ash.

n. a.: Not available.

Table 4. Mixture proportions and fresh properties of sandy flowable slurry.

| Mixture designation | Sd-Ref | Sd-Ref-2 | Sd-WR | Sd-C1 |
|---|---|---|---|---|
| Fibrous residual | (None) | (None) | WR | C1 |
| Cement (kg/m$^3$), C | 16 | 24 | 33 | 33 |
| Class C fly ash (kg/m$^3$), FA | 184 | 177 | 386 | 380 |
| Cementitious materials* (kg/m$^3$), Cm | 200 | 202 | 420 | 413 |
| Sand, SSD (kg/m$^3$), Sd | 1702 | 1716 | 1337 | 1319 |
| Fibrous residual (kg/m$^3$), R | 0 | 0 | 42 | 82 |
| Water (kg/m$^3$), W | 283 | 265 | 297 | 268 |
| C/Cm | 0.08 | 0.12 | 0.08 | 0.08 |
| FA/Cm | 0.92 | 0.88 | 0.92 | 0.92 |
| R/Cm | 0 | 0 | 0.10 | 0.20 |
| Sd/Cm | 8.5 | 8.5 | 3.2 | 3.2 |
| W/Cm | 1.41 | 1.31 | 0.71 | 0.65 |
| R/Slurry | 0 | 0 | 0.02 | 0.04 |
| Flow, 75 × 150 mm cylinder (mm) | 254 | 254 | 225 | 267 |
| Air content (%) | 0.9 | 1.6 | 1.1 | 1.0 |
| Air temperature (°C) | 20 | 20 | 20 | 20 |
| Slurry temperature (°C) | 19 | 20 | 20 | 19 |
| Density (kg/m$^3$) | 2180 | 2180 | 2100 | 2080 |

* Cement plus Class C fly ash.

### 3.2 *Ball-drop diameter*

To be suitable for load application, the ball-drop diameter on CLSM (ASTM D 6024) should be 75 mm (3 in.) or less [ACI 1999]. The ball-drop diameter on the specimens of Mixtures FA-WR and FA-C1 reached about 80 mm in about one week and one day, respectively (Fig. 1). When new CLSM Mixtures FA-WR-2 and FA-C1-2 were made by reducing the W/Cm from about 0.6 to 0.5, the time to reach a ball-drop diameter of approximately 75 mm shortened to about 18 and 1.5 hours, respectively.

Mixture Sd-Ref remained soft for over a week (Fig. 2) due to its relatively high W/Cm and low C/Cm. Mixture Sd-Ref-2 was produced with a lower W/Cm and higher C/Cm than Mixture Sd-Ref. Mixtures Sd-Ref-2, Sd-WR, and Sd-C1 set and became firm within two days.

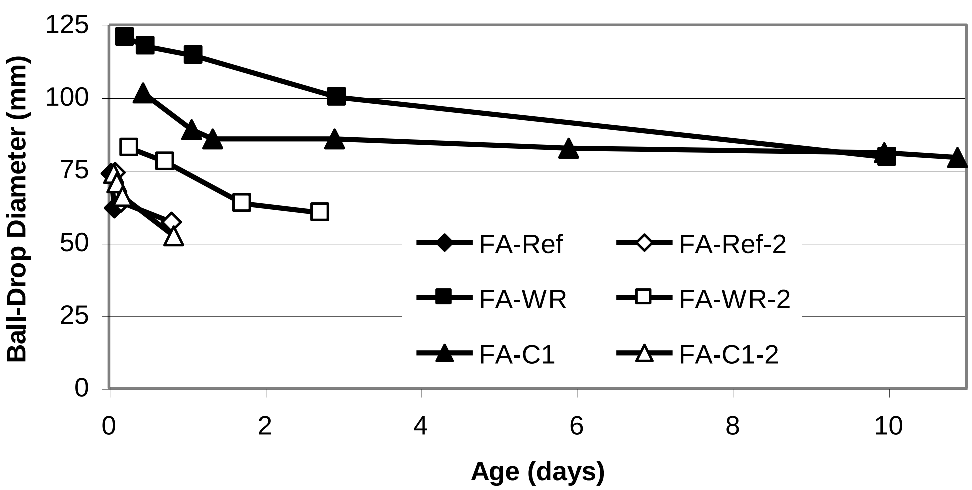


Figure 1. Ball-drop diameter on fly ash flowable slurry.

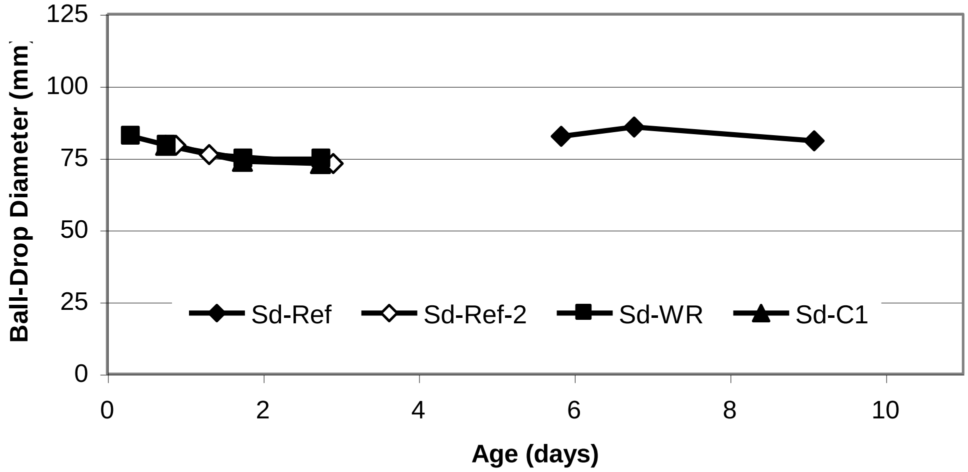


Figure 2. Ball-drop diameter on sandy flowable slurry.

### 3.3 *Compressive strength*

Unconfined compressive strength of CLSM (ASTM D 4832) should be 0.35 to 0.7 MPa (50 to 100 psi) for backfills to allow for manual excavation, 2.1 MPa (300 psi) or less to allow for excavation by using a backhoe, and 2.8 to 8.3 MPa (400 to 1200 psi) for pavement bases [ACI 1999].

The molds for specimens used for compressive strength tests were 100 × 200 mm cylindrical molds. The specimens were stored in cylindrical molds with their tops exposed, in a moist-curing room. On the day of testing, the test specimens were removed from the molds. Then the specimens were dried in the laboratory air for about four hours before they were tested.

Table 5 presents the test results for compressive strength of fly ash slurry mixtures. The fly ash slurry mixtures containing fibrous residuals (Mixtures FA-WR, FA-WR-2, FA-C1, and FA-C1-2) maintained controlled low long-term strength (0.14 to 0.99 MPa at 91 days and 0.55 to 1.44 MPa at 182 days). On the other hand, the ash slurry mixtures FA-Ref and FA-Ref-2 containing no fibrous residuals showed excessively high strength (approximately 9 MPa at 91 days and 9 to 14 MPa at 182 days), due to their relatively low W/cm and high C/Cm.

Table 6 presents the test results for compressive strength of sandy slurry mixtures. Note that at 3 and 7 days, the strength of the sandy mixtures Sd-Ref and Sd-Ref-2 containing no fibrous residuals was very low (soft), lower than that of the sandy mixtures Sd-WR and Sd-C1 containing fibrous residuals. The sandy slurry mixtures containing no fibrous residuals later gained strength at a noticeably higher rate than the sandy mixtures containing fibrous residuals. The long-term strength of the sandy mixtures containing no fibrous residuals was low enough (1.26 and 1.63 MPa at 182 days) to allow for excavation by using a backhoe (between 0.7 and 2.1 MPa). The 182-day compressive strength of Mixture Sd-WR was 1.12 MPa, excavatable by using a backhoe. Mixture Sd-C1 showed low strength from early age (0.13 MPa at 3 days) to later age (0.31 MPa at 182 days), allowing for manual excavation.

Thus, fibrous residuals improved the early-age strength of flowable slurry mixtures and helped to keep the long-term strength at a desirably low level.

Table 5. Compressive strength of fly ash flowable slurry (MPa).

| Age (days) | FA-Ref | FA-Ref-2 | FA-WR | FA-WR-2 | FA-C1 | FA-C1-2 |
|---|---|---|---|---|---|---|
| 3 | 0.45 | 0.46 | 0.16 | 0.45 | 0.10 | 0.68 |
| 7 | 0.48 | 0.43 | 0.20 | 0.60 | 0.10 | 0.73 |
| 28 | 0.63 | 0.66 | 0.26 | 0.66 | 0.12 | 0.90 |
| 56 | 6.52 | 8.52 | 0.28 | 0.89 | 0.13 | 0.88 |
| 91 | 8.82 | 8.87 | 0.32 | 0.99 | 0.14 | 0.91 |
| 182 | 9.35 | 13.84 | 0.71 | 1.14 | 0.55 | n. a. |

n. a.: Not available.

Table 6. Compressive strength of sandy flowable slurry (MPa).

| Age (days) | Sd-Ref | Sd-Ref-2 | Sd-WR | Sd-C1 |
|---|---|---|---|---|
| 3 | 0.08 | 0.08 | 0.17 | 0.13 |
| 7 | 0.09 | 0.07 | 0.17 | 0.14 |
| 28 | 0.47 | 0.79 | 0.23 | 0.15 |
| 56 | 1.07 | 1.22 | 0.58 | 0.18 |
| 91 | 1.12 | 1.38 | 0.88 | 0.18 |
| 182 | 1.26 | 1.63 | 1.12 | 0.31 |

### 3.4 *Hydraulic conductivity (water permeability)*

The hydraulic conductivity of hardened flowable slurry was determined in accordance with ASTM D 5084 using falling head and constant tailwater elevation.

Table 7 presents the test results for hydraulic conductivity of fly ash slurry mixtures. Among the fly ash slurry mixtures, Mixtures FA-Ref and FA-Ref-2 containing no fibrous residuals showed the lowest hydraulic conductivity because of their very high compressive strength.

Table 7. Hydraulic conductivity of fly ash flowable slurry ($10^{-6}$ cm/sec).

| Age (days) | FA-Ref | FA-Ref-2 | FA-WR | FA-WR-2 | FA-C1 | FA-C1-2 |
|---|---|---|---|---|---|---|
| 28 | 2.2 | 1.7 | 23.7 | 13.2 | 12.3 | 2.2 |
| 91 | 1.0 | 0.7 | 17.0 | 6.9 | 9.8 | 2.2 |

Among the fly ash slurry mixtures containing fibrous residuals, Mixture FA-C1-2 showed the lowest hydraulic conductivity ($2.2 \times 10^{-6}$ cm/sec at 91 days) in part due to its relatively high strength. Mixture FA-C1-2 was considerably less permeable to water than Mixture FA-WR, even though the compressive strength of both mixtures was comparable at 28 and 91 days. Similarly, Mixture FA-C1 was less permeable to water than Mixture FA-WR, although Mixture FA-C1 showed lower compressive strength than Mixture FA-WR. Thus, fibrous residual C1 was helpful in reducing the hydraulic conductivity of fly ash slurry.

Table 8 presents the test results for hydraulic conductivity of sandy slurry mixtures. In spite of lower strength at 28 and 91 days, Mixtures Sd-WR and Sd-C1 containing fibrous residuals were generally less permeable to water than Mixtures Sd-Ref and Sd-Ref-2 made without fibrous residuals. Among the sandy slurry mixtures containing fibrous residuals, the lower-strength Mixture Sd-C1 was generally less permeable to water than the higher-strength Mixture Sd-WR. Thus, fibrous residuals, especially C1, were helpful in reducing the hydraulic conductivity of sandy slurry.

Table 8. Hydraulic conductivity of sandy flowable slurry ($10^{-6}$ cm/sec).

| Age (days) | Sd-Ref | Sd-Ref-2 | Sd-WR | Sd-C1 |
|---|---|---|---|---|
| 28 | 12.8 | 16.7 | 13.5 | 8.7 |
| 91 | 10.1 | 12.1 | 6.2 | 6.4 |

## 4 CONCLUSIONS

Based on the data presented, the following general conclusions can be drawn:

1. Fibrous residuals kept fly ash slurry from becoming too cohesive, thus making it easier (less time consuming) to thoroughly mix the slurry-making ingredients and handle fresh slurry.
2. Fibrous residuals prevented rapid setting of the ash slurry mixtures made with Class C fly ash and kept the fresh ash slurry mixtures remain workable while they were being placed.
3. Fibrous residuals helped the fly ash and sandy slurry mixtures to become firm at an early age and maintain a low long-term strength, allowing for future excavation.
4. Fibrous residuals were helpful in reducing the hydraulic conductivity of sandy slurry.

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