Repulping fibrous residuals from pulp and paper mills for recycling in concrete

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ABSTRACT: Recent research has shown that most fibrous residuals can be used to improve the durability of concrete. Cellulose fibers freed up from the residuals reinforce the cement matrix in concrete. The durability of concrete improved in proportion to the ease of repulping the residuals into individual fibers and particles. More fibers can participate in reinforcing the concrete if they are dispersed uniformly. Although dewatering is highly desirable in disposing of the residuals, excessive dewatering may cause some residuals to be less effective in concrete. Pulp and paper mill operators can contribute to much better recycling results and to the growth of the use of these residuals in concrete by providing concrete producers with either sufficiently wet residuals that can be readily repulped or already well-dispersed residuals ready for use in concrete.

Application: By providing wastewater-treatment residuals that can be easily repulped, mills can help commercialize the production of durable concrete reinforced with these fibrous residuals.

In recent research, we discovered that including residuals from wastewater treatment (or sludge) in concrete can greatly improve the durability of concrete [1]. Concrete made with the residuals was about twice as durable as concrete made without any residuals. After a laboratory study, a field construction demonstration was conducted in Wisconsin. Laboratory evaluation of the concrete mixtures from the field demonstration again indicated that the concrete made with residuals was more durable than the concrete made without residuals.

The improvement in durability was attributed to the microfiber reinforcement of concrete by the cellulose fibers from the residuals. Concrete can withstand a relatively large compressive stress (20–70 MPa) and a relatively small tensile stress (3–6 MPa). On the other hand, although cellulose fibers are soft and compressible, they can withstand a very strong tensile stress (300–900 MPa) [2]. In fact, in regard to the ultimate tensile strength, cellulose fibers are as strong as steel or carbon microfibers (600 MPa) [3, 4].

Concrete producers are likely to be interested in further study, development, and trials of concrete reinforced with fibrous residuals from pulp and paper mills. In regard to the expense, the cost of man-made fibers cannot compete with the cost of cellulose contained in sludge from pulp and paper mills. These residuals represent one of the most economical, environmentally friendly, and effective sources of microfibers for use in concrete.

However, for there to be economic benefits, pulp and paper mill operators need to give consideration to the proper preparation of their fibrous residuals for use in concrete. The residuals must be easy to repulp into individual fibers. Better yet, the residuals should be delivered to concrete producers in a well-dispersed condition in a minimal amount of water. This report elucidates the challenge of repulping fibrous residuals for recycling in concrete.

CHARACTERISTICS OF FIBROUS RESIDUALS USED

We used a total of seven sources of fibrous residuals, representing variation in the type of wood fibers and processes used at mills. **Table I** presents the types, physical properties, loss on ignition (LOI), and wood fiber content of the residuals. **Table II** presents the mineral composition of the residuals. **Figure 1** shows scanning electron micrographs (SEM) of oven-dry samples of Residuals C1, C2, I, S, WG, and WV. It appears that it would be difficult to repulp Residuals I and WV.

REPULPING EXPERIMENTS

Mills usually dewater wastewater-treatment residuals before disposing of them in order to reduce their weight and volume [5]. However, excessive dewatering is not favorable for recycling the residuals in concrete. Because of thickening and dewatering at mill plants, the residuals we received contained fibrous clumps that consisted of cellulose fibers, clay (C1, C2, I, S, and WV), and other particles (C2, I, S, WG, and WV). Had these clumps been included in concrete, they would have remained clumps and would have turned into weak spots in the hardened concrete. For fibers to function as strengthening filaments in concrete, they must be separated into well-dispersed individual fibers.

Therefore, we conducted experiments in the concrete laboratory at the University of Wisconsin–Milwaukee (UWM) to establish a practical method of repulping the fibrous residuals. The "pulper" consisted of a 19-L plastic bucket and a high-speed mixer with a rotor positioned above the bottom of the bucket. The rotor blades subjected mixtures of water and fibrous residuals to high-speed rotation.

Initially, each of the seven sources of residuals was subjected to mechanical mixing in room-temperature water for 20 min. From easiest to hardest to repulp, the residuals were: BR, C1, C2, WG, S, and both I and WV together.

It was very easy to repulp Residuals BR and C1. After 20 min of mechanical repulping, Residuals BR and C1 were completely free of clumps. No clumps of fibers could be felt with one's bare hands dipped into the residuals repulped in water. It was relatively easy to repulp Residual C2. It seemed to be relatively easy to repulp Residual WG, but it was not possible to disentangle all of its fibrous agglomerations.

Residual	Type	Fiber source	Solids, %	Specific gravity[a]	Bulk density[b], kg/m³	Avg. fiber length[c], mm	LOI[d], %	Wood fiber, %
C1	primary	virgin	35	1.77	1080	1.22	54.9	43
C2	primary	virgin	31	1.69	1000	1.20	73.1	64
I	primary	recycled	51	2.04	830	0.85	49.7	40[e]
S	primary	recycled[f]	54	2.00	660	1.11	57.9	49[e]
WG	primary	virgin	46	2.17	750	1.51	43.6	35
WV	primary	virgin	41	1.62	570	1.68	82.3	77
BR	reclaim	virgin	30	1.56	450	1.34[g]	99.6	94[e]
Avg.	n.a.	n.a.	41	1.83	760	1.27	65.9	57

[a]Tests were performed on as-received samples. Results expressed on oven-dry basis. [b]As received. [c]Length-weighted. [d]Loss on ignition at 590°C, % of oven-dry (105°C) mass. [e]Estimated as (1.083 loss on ignition at 590°C) – 14.1. The rest determined by infrared analysis. [f]80% recycled, 20% virgin. [g]Using Kajaani FS-100. The rest determined by using a fiber quality analyzer. n.a. = not applicable.

I. Types, physical properties, LOI, and wood fiber contents of the residuals.

Residual	Mineral, % by mass: Calcite	Kaolinite	Magnesite	Quartz	Talc
C1	—	52	—	—	—
C2	15	14	—	5	< 1
I	51	16	—	—	—
S	36	7	7	1	3
WG	63	—	—	2	—
WV	21	2	—	3	—

Calcite=$CaCO_3$. Kaolinite=$Al_2Si_2O_5(OH)_4$. Magnesite=$MgCO_3$. Quartz=SiO_2. Talc=$Mg_3Si_4O_{10}(OH)_2$.

II. Mineralogical composition of the residuals by powder diffraction analysis.

	Before, g^{pan}	After, $g^{4.75}$
Water (18°C)	436	8.1
Detergent	436	8.6
HRWRA		
Naphthalene	436	10.0
Poly-carboxylate	436	10.1
AEA		
Vinsol resin	436	12.6
Synthetic	436	8.0
Average	436	9.6

g^{pan} = amount on a pan, expressed as grams on o.d. basis. $g^{4.75}$ = grams retained on a sieve with 4.75-mm openings.

III. Repulping experiments on Residual I.

	Residual I		Residual W		Residual W in a hot solution	
	Before, $g^{4.75}$	After, $g^{4.75}$	Before, $g^{12.5}$	After, $g^{4.75}$	Before, $g^{12.5}$	After, $g^{4.75}$
Water	51	3.2	8.3	2.8	8.3	0.6
Antiprecipitant	51	3.1	8.3	3.3	8.3	0.7
Antiscalant	51	2.4	8.3	3.8	8.3	0.6
Flocculant	51	3.2	8.3	4.2	8.3	0.4
Average	51	3.0	8.3	3.5	8.3	0.6

$g^{4.75}$=grams retained on a sieve with 4.75 mm openings. $g^{12.5}$=grams retained on a sieve with 12.5 mm openings. [a]Initial temp.=93°C, final temp.=49°C.

IV. Repulping experiments on Residuals I and WV using water, antiprecipitant, antiscalant, and flocculant.

On the other hand, it was hard to repulp Residuals S, I, and WV, and it was especially hard to repulp Residuals I and WV. After mechanical repulping in room-temperature water for 20 min, clumps of fibers could still be seen and felt in the mixtures of each of these three. The main reason for the difficulty was that Residuals S, I, and WV were thoroughly dewatered at mill wastewater-treatment plants.

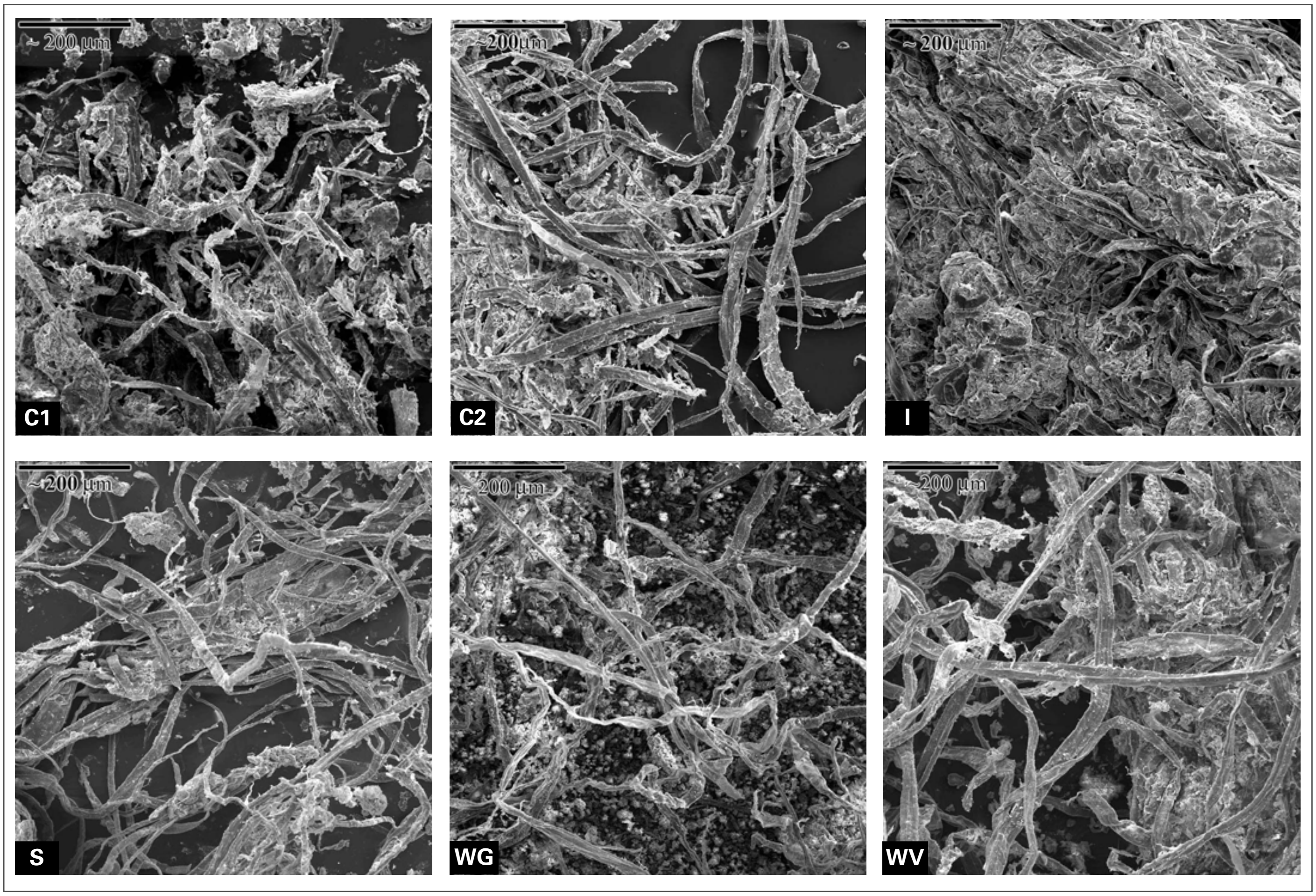
Other factors besides dewatering were the fiber length, the fiber content, and the mineral composition. For example, the Residuals WG, S, I, and WV had higher solids contents than the Residuals BR, C1, and C2. In addition, although Residual WV had an average solids content, WV had the longest average fiber length and a relatively high overall fiber content. (The WV of the second delivery was well dispersed in water because it had not been dewatered at all. Its solids content was only about 7%.)

Next, we tried several types of chemicals to see if they would help in repulping Residuals I and WV. Chemical solutions were prepared by adding to water the following types of chemicals: detergent, high-range water-reducing admixture (HRWRA), air-entraining admixture (AEA), antiprecipitant, antiscalant, and flocculant. HRWRA is a chemical that helps particles in cement to disperse uniformly and mix well with water. AEA is a chemical that is used in generating extremely tiny (microscopic) air bubbles throughout concrete; these air bubbles function as rooms into which microscopic ice in concrete can expand without damaging the concrete.

In addition to adding chemicals, we conducted repulping experiments on Residual WV using both room-temperature water solutions and hot water solutions in order to find out whether or not the use of hot solutions would help. The results of the repulping experiments on Residuals I and WV are presented in **Table III** and **Table IV** as grams retained before and after repulping.

Based on the amount of fibrous clumps retained on a sieve with 4.75 mm openings after repulping, we found none of the chemicals investigated to be helpful in freeing up wood fibers from the residual solids. Using water alone was as good as using any of the chemical solutions. However, repulping in hot-water solutions resulted in better separation and dispersion than did repulping in room-temperature solutions. Overall, the high-speed mixing of residuals in room-temperature water was the most practical and satisfactory means of repulping about three or four (BR, C1, C2, and WG) of the seven sources of residuals.

The conclusions of the repulping experiment are in agreement with the practices at pulp and paper mills [6, 7]. Also the results of the experiments suggest that it becomes extremely hard for concrete producers to repulp the residuals properly once the residuals are dewatered excessively.



1. Micrographs of Residuals C1, C2, I, S, WG, and WV.

REPULPING VS. DURABILITY

We made two groups of concrete mixtures. Each group consisted of a reference mixture containing no residuals and other mixtures containing 0.65% residuals by mass of concrete. The average compressive strength of reference concrete mixtures was about 49 MPa at the age of 28 days. The compressive strength of residual-containing concrete was in the range of 37–48 MPa at 28 days.

As shown in **Table V**, most of the concrete mixtures reinforced with residual fibers showed higher durability than the reference concrete mixtures containing no residuals. In addition, within each group of concrete mixtures, the durability of residual-containing concrete was generally in keeping with the ease of repulping. In general, concrete containing a residual that was easy to repulp was more durable than concrete containing a residual that was difficult to repulp.

Less dewatering of some of the residuals at mill wastewater-treatment plants should result in a better repulping of the residuals, which would lead to much higher durability of concrete. If the well-dispersed Residual WV of the second delivery had been used instead of the half-dried balls of fibers of WV as first delivered, the concrete's performance would have been much better.

A fourfold increase in the compressive strength of a cement paste containing a fibrous residual was obtained when a wet residual was used [8]. This residual had been collected before being thickened and dewatered. The researchers who reported this result attributed the increased strength to superior fiber dispersion.

	Order	Ease of repulping[a]	Durability[b]
Group A	—	—	Ref. A
	1	C1	C1
	2	C2	C2
	3	WG	WV
	4	WV	WG
Group B	—	—	Ref. B
	1	BR	BR
	2	S	S
	3	I	I

[a]Residuals are listed in order of increasing difficulty in repulping. [b]Concrete mixtures are listed in order of descending durability.

V. Relationship between the ease of repulping the residuals and the durability of concrete.

CONCLUSIONS

We have shown that fibrous residuals from pulp and paper mills have the potential to become one of the most economical sources of microfibers for improving the durability of concrete. The easier it is to repulp a residual, the higher the durability of the concrete made with it. For fibrous residuals to function effectively in strengthening concrete, they must be separated reasonably well into individual fibers.

If pulp and paper mills supplied concrete producers with well-repulped residuals, the results would be better in terms of concrete performance. One may ask, what if the residuals are supplied in a dispersed condition in mill wastewater? In other words, what effects would the chemical composition of the mill wastewater have on the properties of concrete? The answer to that question is not known at this point. However, the residuals should be moist enough for ready-mixed concrete producers to repulp the residuals easily. Optimum levels of solids contents have not yet been established for various types of fibrous residuals. **TJ**

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INSIGHTS FROM THE AUTHORS

This research has shown that fibrous residuals can be used to improve the durability of concrete. In the effort to utilize fibrous residuals to reinforce concrete, we first had to establish a practical way to free up cellulose fibers from dewatered residuals. We also had to find the best explanation as to why some sources of residuals greatly improved the durability of concrete and others did not. We discovered that the improvement is proportional to the ease of repulping.

It was difficult to quantify the ease of repulping. We quantified it indirectly by determining the amount of fibrous clumps left after repulping. At first we thought that chemical solutions would be helpful, but we came to realize that mechanical mixing is the most practical method of repulping.

By providing concrete producers with repulped fibrous residuals, mills can present their residuals as a practical and economical source of cellulose fibers for strengthening concrete. More research is needed to determine the target levels of solids contents.

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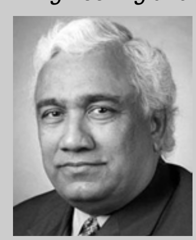

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