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Online sorting of recovered wood waste by automated XRF-technology: Part II. Sorting efficiencies

A. Rasem Hasan [a,1], Helena Solo-Gabriele [a,*], Timothy Townsend [b]

[a] Department of Civil, Architectural, and Environmental Engineering, University of Miami, Coral Gables, FL 33146-0630, USA
[b] Department of Environmental Engineering Sciences, University of Florida, Gainesville, FL 32611-6450, USA

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ABSTRACT

Sorting of waste wood is an important process practiced at recycling facilities in order to detect and divert contaminants from recycled wood products. Contaminants of concern include arsenic, chromium and copper found in chemically preserved wood. The objective of this research was to evaluate the sorting efficiencies of both treated and untreated parts of the wood waste stream, and metal (As, Cr and Cu) mass recoveries by the use of automated X-ray fluorescence (XRF) systems. A full-scale system was used for experimentation. This unit consisted of an XRF-detection chamber mounted on the top of a conveyor and a pneumatic slide-way diverter which sorted wood into presumed treated and presumed untreated piles. A randomized block design was used to evaluate the operational conveyance parameters of the system, including wood feed rate and conveyor belt speed. Results indicated that online sorting efficiencies of waste wood by XRF technology were high based on number and weight of pieces (70–87% and 75–92% for treated wood and 66–97% and 68–96% for untreated wood, respectively). These sorting efficiencies achieved mass recovery for metals of 81–99% for As, 75–95% for Cu and 82–99% of Cr. The incorrect sorting of wood was attributed almost equally to deficiencies in the detection and conveyance/diversion systems. Even with its deficiencies, the system was capable of producing a recyclable portion that met residential soil quality levels established for Florida, for an infeed that contained 5% of treated wood.

1. Introduction

Historically, the most common wood preservative utilized has been an arsenic-based preservative known as chromated copper arsenate (CCA). Arsenic, chromium and copper from the treated wood can be released to the environment or routed to humans by many different mechanisms (Stillwell and Gorny, 1997; Stilwell and Graetz, 2001; Khan et al., 2006; Ochoa-Acuna and Roberts, 2006; Shibata et al., 2007). Each of these three elements has negative impacts on the environment and human health when their concentration is elevated (Adler-Ivanbrook and Breslin, 1998; Stook et al., 2004, 2005; Shalat et al., 2006; Dubey et al., 2007). Due to increased awareness of the negative potential impacts, this chemical as of 2004 was voluntarily phased-out by the wood treatment industry from most residential applications in the U.S. Due to this phase-out of arsenic-based wood preservatives, Cu-based preservatives such as alkaline copper quat (ACQ) and micronized copper quat (MCQ) are expected to dominate the residential treated wood market (Dubey, 2005; Freeman and McIntyre, 2008). Even with the phase-out, the amount of disposed CCA is significant and will increase in the waste stream, to peak to 6–10 million m^3 in the U.S. in 2030 (Jambeck et al., 2007), and peak at 0.8 million m^3 in Canada in 2010 (Cooper, 1994). Up to the year 2000, treated wood waste was found to represent a significant fraction of wood waste (5–30%) received at recycling facilities (Tolaymat et al., 2000; Blassino et al., 2002). This percentage can be larger in some cases where facilities receive complete structures of treated wood as part of their infeed. In order to recycle C&D as fuel (and ultimately dispose the ash in a lined landfill), levels should be less than 5% CCA (Solo-Gabriele et al., 2002), and for recycle as mulch, levels should be less than 0.05% CCA-treated wood; however, it can contain up to 2% ACQ-treated wood (Jacobi et al., 2007). Thus, efforts are needed to identify and separate treated wood from wood waste, so the untreated fraction can be recycled without the added burden from wood preservative chemicals (Solo-Gabriele et al., 2002; Townsend et al., 2003; Shibata et al., 2006; Jacobi et al., 2007).

XRF technology is one technology that is suitable for more accurate assessment of preserved wood that is difficult to identify. XRF technology is a multi-elemental non-destructive technique of metals' inspection (Hou et al., 2004), requiring no prior sample preparation (Solo-Gabriele et al., 2004). The technology is very fast (Wheeler, 1993; Kalnicky and Singhvi, 2001), requiring only

* Corresponding author. Tel.: +1 305 284 2908; fax: +1 305 284 3492.
E-mail address: hmsolo@miami.edu (H. Solo-Gabriele).
[1] Current address: Department of Civil Engineering, An-Najah National University, P.O. Box 7, Nablus, Palestine.

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milliseconds, which makes it suitable for online applications (see Part I of these two paper series for more details about the theory of metal detection via XRF).

Sorting is defined in this research as a three step process: handling of wood, identification, and separation. Specially, for automated sorting by an online XRF system, the analogous terms are conveyance, detection and diversion. Our previous work (see Part I) focused on the second step: detection. The earlier work established the optimum thresholds and measurement times for online real-time detection of preserved wood. This current work focuses on evaluating conveyance (which routes the wood to the XRF detector) and diversion (which routes the detected pieces to the appropriate sorted pile).

The overarching goal of the current study was to evaluate conveyor operational conditions on sorting as a whole (conveyance, detection and diversion), for a full-scale online XRF system. A factorial randomized block design was used to evaluate the effects of belt speed and wood feeding rates on the system. This is the first study to evaluate the conveyance and diversion component of sorting wood, which represents a particular challenge due to the wide range of sizes of this particular waste. Results of this study are discussed in the context of recycling wood as mulch.

2. Methods

2.1. Conveyance, detection and diversion systems

The conveyance equipment consisted of an infeed motorized belt-conveyor and an inclined conveyor (6 m length, 54.2 cm effective width, and 297 cm height) installed perpendicular to the discharge end of the infeed conveyor (3 m length, 108 cm width, and 165 cm highest end above ground). The infeed conveyor was designed to convey wood to the XRF-detection unit, and the inclined conveyor to move the untreated wood to a separate pile for further processing. The XRF-detection system was installed on the top of the infeed conveyor. After inspection, treated wood was then discharged from the end of the infeed conveyor by a slide-way diverter bypassing the inclined conveyor (Fig. 1) via a stationary slide-way connector. Steel shields were installed on the inclined conveyor to minimize the effects of bouncing and rolling of wood pieces once diverted. The time to open the slide-way diverter after detection was set equal to the delay time, the time for the wood piece to move from the inspection point to the discharge end of the conveyor. The delay time is a function of the belt speed and the distance from the XRF inspection point on the belt to the discharge end of the infeed conveyor.

Identification of preserved wood by XRF focused on the detection of As and/or Cu presence in wood. The detection of As and Cu, indicated the presence of arsenical preservatives in the wood, most likely CCA. The presence of Cu only indicated the presence of copper-based preservatives such as alkaline copper quat (ACQ), among other copper-based preservatives (AWPA, 2008).

Based on Part I of this two paper series (Hasan et al., 2011), the operational detection thresholds for As and Cu were chosen as 0.02 and 0.05, respectively, and the measurement time of the XRF system was chosen as 250 ms.

2.2. Infeed wood characteristics

Two sets of wood were used as infeed and each consisted of a 1000 pieces of wood and differed from each other by the proportion of untreated wood versus treated wood, as defined by the number of pieces in each category. One set was characterized by 50% untreated wood and 50% treated wood (50:50) and the other set was characterized by 95% untreated wood and 5% treated wood (95:05). The group of 500 pieces of treated wood used in the 50:50 set was the same as used in Part I (Hasan et al., 2011). Thus, this infeed differed from the infeed used in the previous study by the addition of 500 untreated wood pieces which were randomly mixed with the treated pieces. The 50:50 set was chosen as a balance point to evaluate treated versus untreated wood sorting when the proportions were equal, thus removing the effect of treated wood fraction in discriminating between treated wood versus untreated wood sorting efficiencies. The 95:05 set was chosen because this was the proportion observed at wood recycling facilities which practice visual sorting (Jacobi et al., 2007). Treated wood included As-based treated wood, Cu-based (non-arsenical) treated wood, and other-treated wood which were extremely

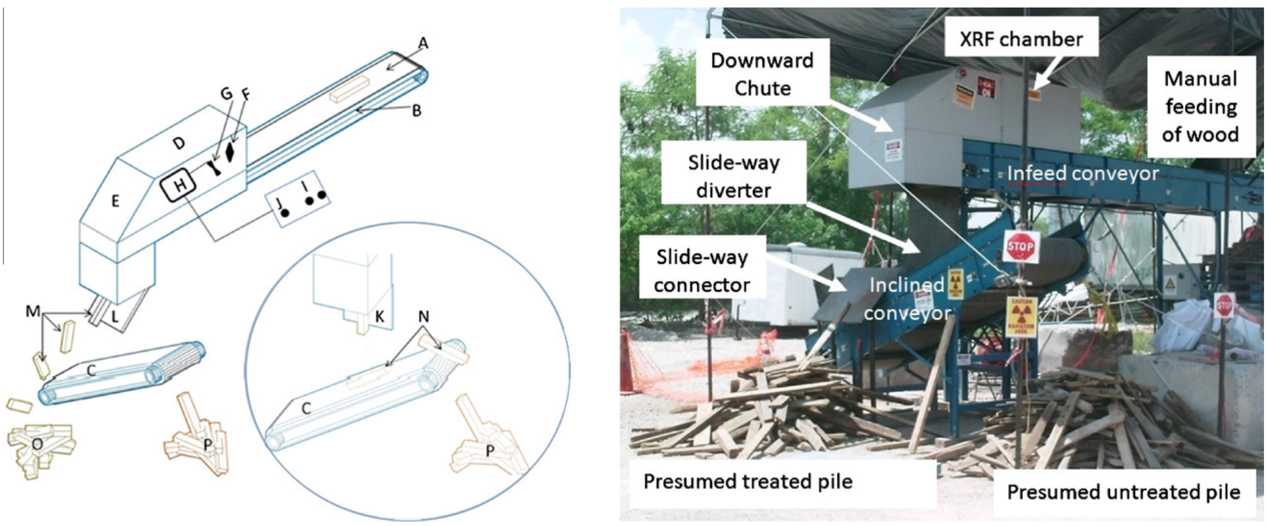

Fig. 1. The XRF detection and sorting system (photo right and schematic left). The dimensions of the motorized infeed belt-conveyor are: 6 m length, 54.2 cm width, and 297 cm height, and for the inclined conveyor: 3 m length, 108 cm width, and 165 cm highest end above the ground. The slide-way diverter is made of a steel sheet with dimensions as $81.3 \times 81.3 \times 0.6$ cm. Legend of the schematic diagram: (A) infeed wood, (B) infeed motorized belt-conveyor, (C) discharge (inclined) conveyor, (D) XRF chamber, (E) downward wood chute, (F) X-ray (source) tube, (G) X-ray detector, (H) digital pulse processing unit, (I) computer-software, (J) control panel, (K) slide-way diverter (closed position), (L) slide-way diverter (open position), (M) As/Cu-treated wood piece, (N) untreated wood piece, (O) presumed treated wood pile, (P) presumed untreated wood pile.

weathered wood samples that contained elevated levels of chromium and low or undetectable levels of arsenic. The three groups of treated wood were denoted as As-, Cu-, and O-treated (Table 1).

The configuration of the XRF chamber on the top of the infeed conveyor permitted for sorting wood of lengths less than or equal 150 cm. Given this constraint, 500 pieces of untreated wood were randomly collected at recycling facility located in South Florida, USA, thus reflecting the distribution which would be observed at full-scale facility. In order to minimize the effects from the different sizes of wood pieces, each portion of the wood infeed used had (treated and untreated) the same length distribution, since the length was an important factor to affect proper sorting. The length distribution of the 500 treated pieces used in the treated portion of the 50:50 set (Fig. 2), the other 500 untreated pieces of the 50:50, the 950 untreated pieces and the 50 treated pieces of the 95:05 set, all had a bell-like shape resembling the normal distribution shifted towards positive range. Metal contents of the 500 treated wood pieces had the same distribution described in the first part of this two paper series.

2.3. Experimental design

Experiments were completed using a randomized factorial block design without replication (Hicks and Turner, 1999) in an effort to evaluate the wood sorting efficiency, metal recovery, and the composition of each sorted pile (Fig. 3). A combination of two different factors was chosen randomly at each experimental run. These factors included wood feeding rate, FR of 20, 40 and 60 pc/min (simulating one, two and three persons on a picking line, assuming that it would take an average of 3 s to pick a piece of wood and transfer it to the system) and belt speed of the infeed conveyor, BS of 0.25, 0.375 and 0.5 m/s (to simulate the speeds of readily available commercial conveyors). Delay times (1.7, 1.95 and 2.2 s) were changed accordingly with the belt speed.

Nine experiments were conducted by sorting 1000 pieces of wood of the 50:50 infeed set and four experiments of the 95:05 infeed set. After each experimental run, wood pieces in the two piles (presumed treated and presumed untreated) were manually sorted to confirm actual treatment, counted for number of pieces, and weighed using an industrial platform scale with a resolution of plus or minus 0.5 kg. Within each "presumed" pile from the XRF system, wood was identified as either truly treated or truly untreated. Treated wood in both sorted piles were further separated into various categories including As-, Cu-, and O-treated wood. Manual sorting of the presumed treated and presumed untreated wood was based upon the identification code established for each wood piece thus allowing the researchers to track each individual piece of wood within the set of 1000.

2.4. Data analysis

2.4.1. Sorting efficiencies

Wood sorting efficiencies were calculated for treated wood (TW) and untreated wood (UW) pieces for each experimental run based on the number and weight (SEN and SEW) (Fig. 3). Sorting efficiency was calculated as ratio between the number and weight of correctly diverted pieces in each pile to the total in the infeed pile on a percent basis. This principle was extended for the As-, Cu-, and O-treated wood.

2.4.2. Mass recovery

Metals' mass recovery (R) is a measure of the metal mass diverted from the wood recycling stream, diverted away from the presumed untreated pile (Fig. 3). These percentages were calculated for As, Cu, and Cr by tracking each coded treated wood piece

Table 1
Treated wood chemical-contents for wood infeeds used in this study. Number of untreated pieces in the 50:50 infeed was 500 and the number of untreated pieces in the 95:05 infeed was 950.

Infeed type	No. of treated pieces		Arsenic content (g)		Copper content (g)		Chromium content (g)	
	50:50	95:05	50:50	95:05	50:50	95:05	50:50	95:05
As-treated	417	44	1252	137	682	50	736	71
Cu-treated[a]	66	5	2.9	0.1	403	7	11.6	0.3
O-treated[b]	17	1	0.74	0.01	3.74	0.00	4.72	0.13
Total	500	50	1256	137	1089	57	752	71

[a] Wood containing Cu and not As.
[b] Extremely weathered pieces containing elevated levels of Cr and not identified as As- or Cu-treated pieces.

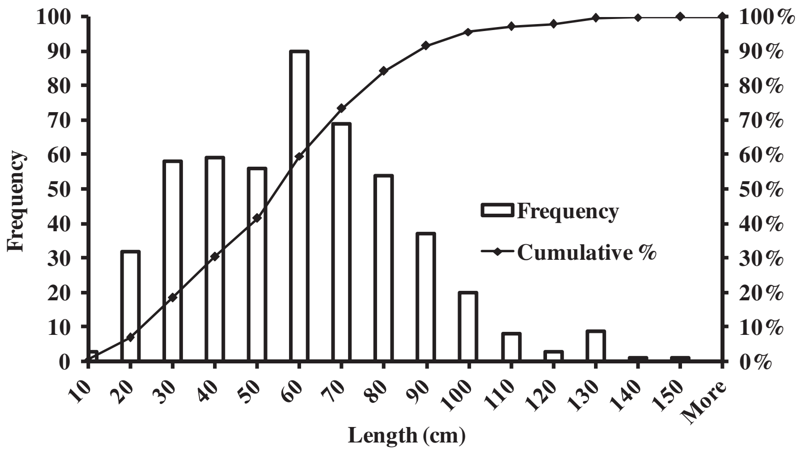

Fig. 2. Wood distribution based on number of pieces according to their length for the 500 treated wood pieces. The x-axis label corresponds to the upper limit of the bin.

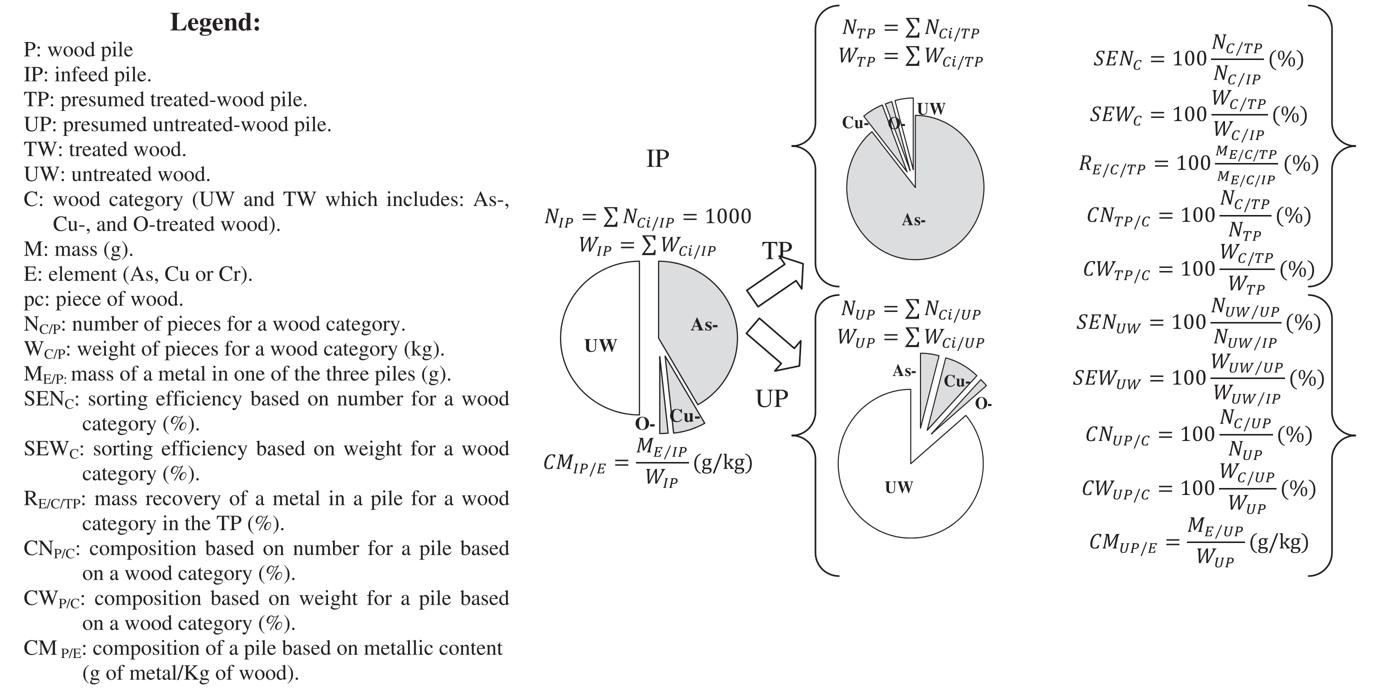

Fig. 3. Calculation formulas for sorting efficiencies based on number (SEN) and weight (SEW), metals mass recovery (R), and sorted piles' composition based on number (CN), weight (CW) and metallic contents (CM).

and summing up the metals content in the presumed treated pile and dividing by the total mass in the corresponding infeed (Table 1). *R* values (%) were computed for As, Cu, and Cr, even though Cr was not used as a target metal for XRF inspection. The Cr-content was tracked because the Cr mass for each wood piece was included in the applied coding system.

2.4.3. Sorted piles' composition

Each presumed sorted pile was analyzed for its composition based on number of pieces and weight (CN and CW) (Fig. 3). Sorted pile composition was calculated based on the percentage of each wood category (number or weight) that ended up in the pile to the total number of pieces in the pile. Composition was also evaluated based on metallic content (CM) (g/kg) for the presumed untreated pile as a measure of the metals content that would be anticipated for recycled wood as a result of this process. CM is defined as the ratio between the total of each metal mass to the total wood weight of the presumed untreated pile.

2.4.4. Statistical inferences

The randomized factorial block designs for the 50:50 and 95:05 experiments were analyzed by the generalized linear model of the analysis of variances (two-way ANOVA) by SigmaStat program (SigmaStat for windows version 3.5, © Systat Software Inc., Richmond, CA, USA) as 3^2 factorial experiments for the 50:50 set and as 2^2 for the 95:05 set. Two variable factors, belt speed (BS) and feeding rate (FR), were evaluated for their effects on the system response. The operational thresholds and measurement time of the XRF system were kept as fixed factors, and the different types of wood pieces in the infeed pile were randomly mixed before each experimental run and randomly fed to the sorting system. The sensitivity of the tests were carried at $\alpha = 0.05$. The response data was checked for its normality (using the Kolmogorov–Smirnov test) and equality of variances assumptions, both at *p* values greater than 0.05. All the reported values in Section 3 were verified to pass these two tests. Significant differences at different treatment levels were further evaluated by a Tukey test as a multiple comparison procedure with *p* value less than 0.05.

3. Results

3.1. Sorting efficiency

3.1.1. UW sorting efficiency

The untreated wood sorting efficiency for the 50:50 set decreased significantly by number of pieces ($p < 0.01$), and by weight ($p < 0.001$) as feeding rate increased, with a more significant change as FR increased from 20 to 40 (pc/min) than from 40 to 60 (pc/min) ($p < 0.016$). Based on number, sorting efficiencies of untreated wood measured (average ± SD) at 95.9 ± 1.2%, 79.1 ± 5.6%, and 73.6 ± 8.3% for the 50:50 infeed. Based on weight, the corresponding sorting efficiencies were 93.2 ± 2.8%, 79.3 ± 5.6%, and 72.4 ± 7.2% (Fig. 4). For the 95:05 infeed, the measured sorting efficiencies by number of untreated wood decreased significantly ($p < 0.05$) as feeding rate increased, and measured at 96.1 ± 1.3% and 93.2 ± 1.6% for FR of 20 and 60 (pc/min), respectively. The measured sorting efficiencies by weight also decreased with increasing FR as 94.1 ± 0.9% and 91.1 ± 1.5%, respectively, but this decrease was not significant.

When evaluating the effects of belt speed, the untreated wood sorting efficiency for the 50:50 infeed decreased slightly (from 80.1 ± 12.5% to 77.4 ± 11.6%) as BS increased from 0.25 to 0.375 m/s, but increased significantly (to 87.3 ± 7.8%, $p < 0.021$) as BS increased to 0.5 m/s. Similar trends were observed for changes in belt speed for the 95:05 set, but these changes were not significant.

3.1.2. TW sorting efficiency

Sorting efficiencies for treated wood based on numbers and weights showed no significant change at the different applied levels of FR and BS (Table 2). The measured sorting efficiency for treated wood for all nine experimental runs of the 50:50 set was 83.9 ± 3.0% based on number and was 88.6 ± 3.5% based on weight.

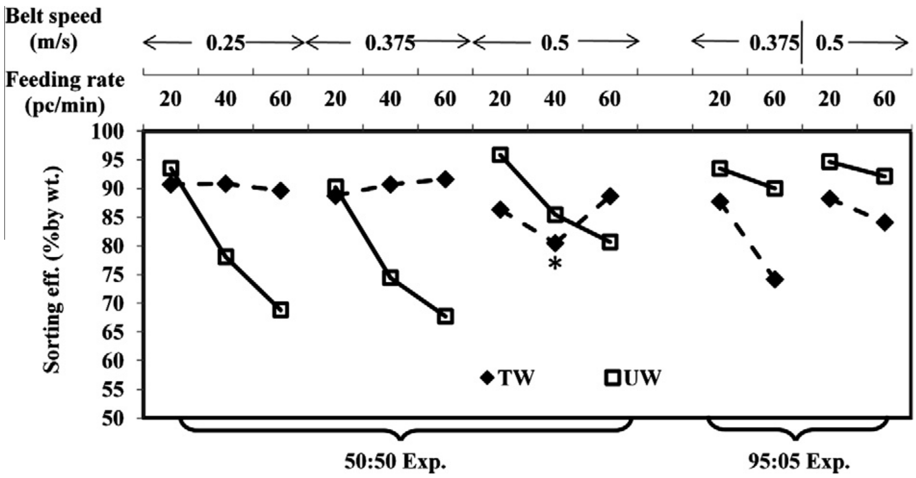

Fig. 4. Treated and untreated wood sorting efficiencies based on wood weight. The "*" corresponds to a jam during the operation of the experiment which resulted in reduced sorting efficiency based on number (SEN_{TW}) and weight (SEW_{TW}). TW, treated wood; UW, untreated wood.

For the 95:05 set, the sorting efficiency for treated wood for all four experimental runs was 80.5 ± 7.2% based on number and was 83.7 ± 6.3% based on weight.

When evaluating subsets of the treated wood infeed, the measured sorting efficiency for As-based wood for the 50:50 set was above 90% (93.4 ± 2.9% based on number and was 95.8 ± 3.0% based on weight). For the 95:05 set, the measured efficiency of As-treated wood was near 90% (88.1 ± 7.3% based on number and was 91.9 ± 5.5% based on weight). On the contrary, sorting efficiency for Cu-based pieces were lower (35.9 ± 12.5% based on number and 43.1 ± 12.1% based on weight for the 50:50 set and 30 ± 12.0% based on number and 30.7 ± 15.1% based on weight for the 95:05 set). The measured sorting efficiencies for O-treated pieces were also relatively low (38.6 ± 9.4% based on number and 29.1 ± 8.5% based on weight for the 50:50 set).

3.2. Mass recovery

3.2.1. Arsenic recovery

The above sorting efficiencies achieved a recovery of arsenic as 96.7 ± 2.1%, for the 50:50 set and as 93.3 ± 8.5% for the 95:05 set, with no significant differences among the applied belt speeds and feeding rates. Arsenic was mostly recovered due to correctly sorting the As-based pieces (96.8 ± 2.1% and 93.3 ± 8.6%, for the 50:50 and 95:05, respectively). For the Cu- and O-treated pieces a lower fraction of arsenic was recovered (49.2 ± 13.2% and 59.6 ± 32.3% for the 50:50 experiments).

3.2.2. Copper recovery

Even though the sorting efficiency of Cu-based pieces was low, the recovery of Cu metal mass was high (83.4 ± 6.9% recovery for the 50:50 set and 87.7 ± 8.6% recovery for the 95:05 set). The majority of the Cu was removed as a result of the arsenic detection within the As-based pieces due to the predominance of the CCA preservative which contains both As and Cu. The amount of Cu that was recovered within As-based pieces was higher (97.8 ± 1.4%, 94.4 ± 6.3% for the 50:50 and 95:05 sets, respectively) than that within the Cu-based ones (59.6 ± 17.5% and 40.9 ± 36.1% for the 50:50 and 95:05 sets, respectively).

3.2.3. Chromium recovery

Chromium was recovered from the infeed mostly within the As-based pieces. The recovery for Cr within the As-based pieces was 96.3 ± 2.3% and 93.1 ± 7.4% for the 50:50 and 95:05 sets, respectively. The recovery for Cr within the Cu-based pieces was lower at 50.3 ± 12.8% and 17.3 ± 7.7% for the 50:50 and 95:05 sets, respectively. In total Cr was recovered at 95.2 ± 2.3% and 92.6 ± 7.4% from the infeed for the 50:50 and 95:05 sets, respectively.

3.3. Sorted piles' composition

3.3.1. UP composition

No significant difference in the composition of the presumed untreated pile was observed at the different applied FR and BS for the 50:50 and 95:05 sets. The presumed untreated pile was dominated by untreated wood and the untreated wood fraction was higher for the 95:05 set than the 50:50 set due to the large difference in the number of treated wood pieces in the infeed. For the 50:50 set the composition of the untreated wood pieces in the presumed untreated pile was 83.7 ± 3.3% based on number and was 83.7 ± 3.5% based on weight. For the 95:05 set, composition of the untreated wood pieces in the presumed untreated pile was higher at 98.9 ± 0.4% based on number and 98.8 ± 0.6% based on weight. The composition of treated wood in the presumed untreated pile was the complement of 100%.

3.3.2. TP composition

The composition of the presumed treated pile for the 50:50 set, by number, decreased significantly ($p < 0.001$) for treated wood (and increased for untreated wood) as the different levels of the applied feeding rates were increased (95.4 ± 1.3%, 80.0 ± 3.5%, and 76.8 ± 5.7% for FR of 20, 40, and 60 pc/min), with more significant changes as FR increased from 20 to 40 pc/min than 40 to 60 pc/min ($p < 0.003$). The same trends were observed for the TP composition based on weight ($p < 0.001$) (94.9 ± 1.9%, 85.9 ± 2.5%, and 82.4 ± 3.5% for FR of 20, 40, and 60 pc/min), with a more significant change from 20 to 40 pc/min ($p < 0.001$) (Fig. 5). When evaluating the effects of BS, the composition of the presumed treated pile as treated wood for the 50:50 set by weight, decreased slightly (from 87.3 ± 7.3% to 85.4 ± 6.7%) as belt speed increased from 0.25 to 0.375 m/s, but increased significantly (to 90.5 ± 5.4%, $p < 0.012$) as belt speed increased to 0.5 m/s. Similar trends, but insignificant, were observed for composition by number (87.3 ± 7.3% to 85.4 ± 6.7% to 90.5 ± 5.4%). The untreated wood composition changed accordingly as complement of 100.

For the 95:05 set, similar trends were observed with a significant ($p < 0.029$) decrease in composition for treated wood by

Table 2
Results of experimentation of the 50:50 infeed and the 95:05 infeed. Statistics in the table correspond to nine experiments for the 50:50 set and four experiments for the 95:05 set.

Property	Unit	50:50 experiment					95:05 experiment				
		Average	SD	Range	$(p<)^a$ FR	$(p<)^a$ BS	Average	SD	Range	$(p<)^a$ FR	$(p<)^a$ BS
SEN_{UW}	%(pc/pc)	82.9	11.3	66.6–97.0	0.01	0.104	94.5	1.9	92.1–96.6	0.05	0.067
SEN_{TW}	%(pc/pc)	83.9	3.0	77.0–87.2	0.39	0.159	80.5	7.2	70–86	0.42	0.605
SEN_{As-}	%(pc/pc)	93.4	2.9	86.1–95.4	0.77	0.431	88.1	7.28	77.3–93.2	0.50	0.605
SEN_{Cu-}	%(pc/pc)	35.9	12.5	21.2–63.6	0.09	0.175	30	12	20–40	–	–
SEN_{O-}	%(pc/pc)	38.6	9.4	23.5–52.9	0.82	0.655	–	–	–	–	–
SEW_{UW}	%(kg/kg)	81.6	10.4	67.7–95.9	0.001	0.021	92.6	2.0	90.0–94.7	0.10	0.174
SEW_{TW}	%(kg/kg)	88.6	3.5	80.5–91.6	0.56	0.129	83.7	6.3	74.6–88.2	0.31	0.467
SEW_{As-}	%(kg/kg)	95.8	3.0	88.3–98.2	0.75	0.336	91.5	5.5	84.0–95.7	0.33	0.514
SEW_{Cu-}	%(kg/kg)	43.1	12.1	31.9–69.2	0.31	0.144	30.7	15.1	14.3–50.0	–	–
SEW_{O-}	%(kg/kg)	29.1	8.5	20.0–42.9	0.66	0.759	–	–	–	–	–
$R_{As/TW/TP}$	%(g/g)	96.7	2.1	91.7–98.8	0.75	0.244	93.3	8.5	80.6–99.1	0.37	0.443
$R_{Cu/TW/TP}$	%(g/g)	83.4	6.9	75.0–92.0	0.68	0.19	87.7	8.6	75.4–95.4	0.55	0.746
$R_{Cr/TW/TP}$	%(g/g)	95.2	2.3	89.8–97.4	0.65	0.166	92.6	7.4	82.5–98.5	0.23	0.431
$R_{As/As-/TP}$	%(g/g)	96.8	2.1	91.2–98.9	0.74	0.25	93.3	8.6	80.7–99.1	0.38	0.443
$R_{As/Cu-/TP}$	%(g/g)	49.2	13.2	35.1–76.5	0.71	0.134	15.0	12.3	1.7–28.3	0.81	1
$R_{As/O-/TP}$	%(g/g)	59.6	32.3	8.9–83.0	0.44	0.99	–	–	–	–	–
$R_{Cu/As-/TP}$	%(g/g)	97.8	1.4	94.9–99.3	0.61	0.105	94.4	6.31	85.6–99.7	0.24	0.375
$R_{Cu/Cu-/TP}$	%(g/g)	59.6	17.5	38.3–83.7	0.64	0.244	40.9	36.1	4.5–77.3	0.88	1
$R_{Cu/O-/TP}$	%(g/g)	16.5	27.3	0.35–86.2	0.51	0.501	–	–	–	–	–
$R_{Cr/As-/TP}$	%(g/g)	96.3	2.3	91.1–98.7	0.59	0.175	93.1	7.4	82.9–99.0	0.23	0.434
$R_{Cr/Cu-/TP}$	%(g/g)	50.3	12.8	37.2–74.7	0.81	0.259	17.3	7.7	8.1–26.6	0.39	1
$R_{Cr/O-/TP}$	%(g/g)	25.6	11.1	11.6–46.0	0.29	0.864	–	–	–	–	–
$CN_{TP/UW}$	%(pc/pc)	16.0	9.3	3.6–27.7	0.003	0.115	55.4	10.3	43.2–68.2	0.029	0.039
$CN_{TP/TW}$	%(pc/pc)	84.0	9.3	72.3–96.5	0.003	0.115	44.6	10.3	31.8–56.8	0.029	0.039
$CN_{TP/As-}$	%(pc/pc)	78.1	9.9	64.0–91.7	0.004	0.109	42.9	9.5	30.9–54.1	0.042	0.052
$CN_{TP/Cu-}$	%(pc/pc)	4.6	1.1	3.3–7.0	0.23	0.313	1.7	0.9	0.91–2.70	0.08	0.331
$CN_{TP/O-}$	%(pc/pc)	1.3	0.3	0.7–1.8	0.93	0.578	–	–	–	–	–
$CN_{UP/UW}$	%(pc/pc)	83.7	2.3	78.3–86.2	0.36	0.473	98.9	0.4	98.0–99.0	0.41	0.585
$CN_{UP/TW}$	%(pc/pc)	16.3	2.3	13.8–21.7	0.36	0.473	1.2	0.6	0.82–2.04	0.41	0.585
$CN_{UP/As-}$	%(pc/pc)	5.6	2.4	3.6–11.0	0.60	0.617	0.6	0.4	0.33–1.12	0.49	0.594
$CN_{UP/Cu-}$	%(pc/pc)	8.5	1.0	6.0–9.7	0.43	0.558	0.4	0.1	0.32–0.45	0.003	0.047
$CN_{UP/O-}$	%(pc/pc)	2.1	0.4	1.6–3.0	0.63	0.434	0.1	0.0	0.1–0.11	0.04	0.044
$CW_{TP/UW}$	%(kg/kg)	12.3	6.2	3.4–20.2	<.001	0.012	56.1	8.6	47.7–65.0	0.02	0.098
$CW_{TP/TW}$	%(kg/kg)	87.7	6.2	79.8–96.6	<.001	0.012	43.9	8.6	35.0–52.3	0.02	0.098
$CW_{TP/As-}$	%(kg/kg)	82.3	6.6	72.4–91.3	0.002	0.029	41.6	7.3	34.1–50.0	0.05	0.159
$CW_{TP/Cu-}$	%(kg/kg)	5.0	1.0	3.9–7.1	0.73	0.237	1.3	0.7	0.81–2.33	0.41	0.396
$CW_{TP/O-}$	%(kg/kg)	0.4	0.1	0.2–0.6	0.50	0.482	–	–	–	–	–
$CW_{UP/UW}$	%(kg/kg)	83.7	3.5	75.2–87.7	0.49	0.337	98.8	0.6	98.0–99.2	0.40	0.409
$CW_{UP/TW}$	%(kg/kg)	16.3	3.5	12.3–24.8	0.49	0.337	1.2	0.6	0.82–2.04	0.40	0.409
$CW_{UP/As-}$	%(kg/kg)	5.2	3.2	2.4–12.8	0.71	0.499	0.5	0.4	0.27–1.08	0.38	0.496
$CW_{UP/Cu-}$	%(kg/kg)	9.8	1.4	6.4–10.9	0.78	0.702	0.4	0.3	0.27–0.82	0.49	0.334
$CW_{UP/O-}$	%(kg/kg)	1.3	0.3	0.9–1.9	0.23	0.615	0.2	0.1	0.14–0.28	0.54	0.52
$CM_{UP/As}$	g/kg	0.11	0.06	0.04–0.23	0.61	0.352	0.01	0.02	0.01–0.04	0.22	0.426
$CM_{UP/Cu}$	g/kg	0.47	0.17	0.26–0.69	0.57	0.468	0.01	0.01	0.00–0.01	0.53	0.748
$CM_{UP/Cr}$	g/kg	0.1	0.04	0.05–0.17	0.33	0.301	0.01	0.01	0.00–0.02	0.37	0.441

[a] Significant when $p < 0.05$.

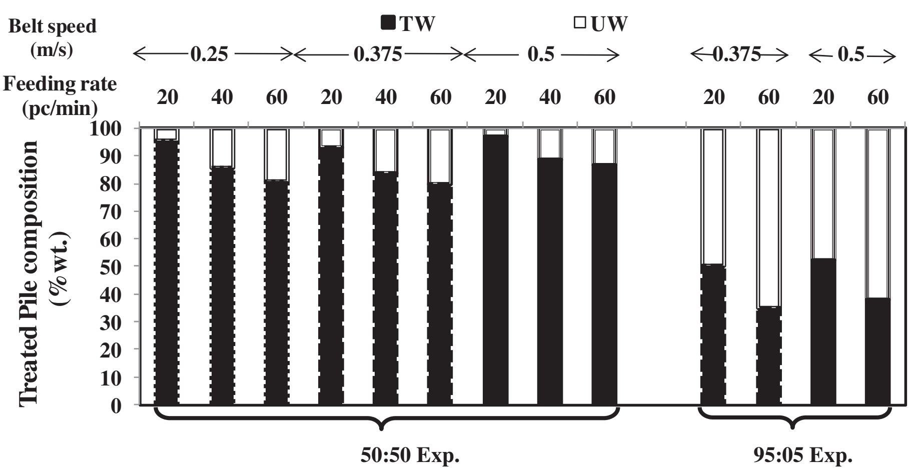

Fig. 5. Composition of presumed treated pile based on wood weight. TW, treated wood; UW, untreated wood.

number (51.7 ± 7.1% for FR of 20 pc/min and 37.5 ± 8.0% for FR of 60 pc/min) and weight (51.2 ± 1.6% for FR of 20 pc/min and 36.8 ± 1.9% for FR of 60 pc/min) as the FR increased.

When evaluating the effects of belt speed, the composition of the presumed treated pile as treated wood, increased significantly by number (from 39.3 ± 10.6% to 50 ± 9.6%, $p < 0.039$), and insignificantly by weight (from 42.5 ± 10.6% to 45 ± 10.0%, $p < 0.098$) as belt speed increased from 0.375 to 0.5 m/s. The untreated wood composition changed accordingly as complement of 100.

These observations were strongly affected by the composition of As-based portion of treated wood ($p < 0.004$ for 50:50 and $p < 0.05$ for 95:05, by number and weight, respectively) since As-based pieces represented the bulk of the treated wood in the infeed (83.4% for the 50:50 and 88% for the 95:05 experiments).

4. Discussion

4.1. Sorting efficiency

Sorting efficiencies of both untreated and treated wood based on numbers and weights were generally above 67% for the 50:50 set and above 70% for the 95:05 set, although efficiencies increased for specific FR and BS settings.

4.1.1. UW sorting efficiency

Observations showed that incorrect diversion of UW was due, in large part, to overlapping of wood on the conveyor belt or wood bouncing from the inclined conveyor to the TP instead of being carried by the inclined conveyor to the UP. FR predominantly impacted overlapping of wood (observed for wood pieces that were generally less than 80 cm in length) whereas BS predominantly impacted the bouncing of wood (observed for wood pieces that were generally longer than 80 cm in length). As FR increased, the amount of wood overlapped with TW on the conveyor belt became frequent. The sorting system was designed to sort towards the presumed treated pile, so untreated wood which overlapped the treated wood on the infeed conveyor was diverted to the treated wood pile and counted as incorrectly diverted. For UW pieces of length less than 80 cm, the fraction of incorrectly diverted pieces by number (as % of the original UW in the infeed) changed significantly for both experimental sets as FR was increased. These pieces are believed to be incorrectly diverted due to overlapping with TW because of the increased probability for UW to overlap TW as FR increases.

For BS, increases in BS resulted in two complementary phenomena which improved sorting efficiencies. The first and most significant was less bouncing of TW towards the UP and secondly an increase in BS also resulted in a decrease in wood overlapping. With respect to bouncing of wood, when BS was high, long UW pieces were dropped on the inclined conveyor and hit the shielding at the farthest end of the conveyor or the stationary slide-way connector, where they lost their momentum and fell on the conveyor and moved correctly toward the UP. At the lower BS, wood dropped straight down on its smallest edge hitting the conveyor and this would then bounce above the shielding toward the TP. So here the key was that the increased forward momentum of the wood at higher belt speeds resulted in longer pieces of wood hitting the shielding of the inclined conveyor in such a way that it would fall back towards the inclined conveyor thus promoting correct sorting toward the UP.

4.1.2. TW sorting efficiency

Unlike the significant change of UW sorting efficiencies according to the applied operational conditions of the conveyance system, TW wood sorting efficiencies were not impacted by operational conditions of the conveyance system. TW sorting efficiencies were more strongly impacted by detection parameters (Part I of this two paper series) as opposed to conditions of the conveyance system.

High As and Cu concentration pieces (As > 1000 and Cu > 4000 ppm) were correctly diverted all the time. Correct diversion of very low As and Cu concentration-treated wood pieces or As and Cu free preserved wood (as found among some of the O-pieces), is believed to occur due to overlapping and bouncing effects as untreated wood, rather than to correct detection. On the contrary, some small treated pieces (<10 cm in length) were found to be diverted correctly by the diverter, but would bounce from the diverter and would fall on the inclined conveyor and would be incorrectly diverted to the untreated pile; such pieces should not have a major effect on the sorting efficiency based on weight or metallic contents, but can have a more significant effect when sorting efficiency is based on the number of wood pieces. Overall, because of all of these competing phenomena, TW sorting efficiencies did not change significantly with FR or BS.

4.2. Mass recovery

In summary, total As, Cu, and Cr mass recovery from all treated wood were 96.8 ± 2.1%, 83.3 ± 6.9%, and 95.2 ± 2.3%, respectively, for the 50:50 set. For the 95:05 set, the respective As, Cu, and Cr recoveries were 93.3 ± 8.5%, 87.7 ± 8.6%, and 92.6 ± 7.4%.

Within the treated wood portion, the highest sorting efficiencies among all types of preserved wood used in this experiment was observed within As-treated wood, and thus As had the highest mass recovery. The reason behind this was twofold. The first reason was operational as the detection system was sensitive to As as evidenced by the low operational threshold for As which was 150% less than that of Cu. The second reason was due to the composition of the majority of the wood as CCA; most of the As-based pieces contained both As and Cu, and so each CCA piece has a chance to be detected based on the content of one or two of these metals.

In addition to the sort based on As, which recovers a considerable amount of Cu and Cr, additional recoveries were facilitated by the detection of Cu-treated wood, especially the Cu-based pieces with high concentrations of Cu.

4.3. Sorted piles' composition

The analysis of the composition of each presumed treated and untreated pile provides additional evidence for the success of recovered wood sorting by XRF technology. The concern after the sorting process, is the amount (or percentage) of the targeted metals that goes to the recycling stream of the untreated pile, and the amount of the untreated wood that will be diverted into environmentally safe landfills or wood-monofills and hence occupying space that can be designated for treated wood.

4.3.1. TP composition

The major component of the presumed treated pile in the 50:50 experiments was As-treated wood, and for the 95:05 experiments was UW. The reason for this observation is because of the large differences in the infeed composition. Fifty percent of the wood infeed for the 50:50 set was composed of treated wood and thus the probability of getting untreated wood within the treated wood pile was much smaller than for the 95:05 set which had only 5% treated wood and 95% untreated wood. Specifically, for the 95:05 experiments, the presumed treated pile was composed of 44% untreated wood based upon number (Fig. 6 is an example for one of the experimental runs of the 95:05 set). Because of the overwhelming number of untreated wood pieces in the 95:05 infeed,

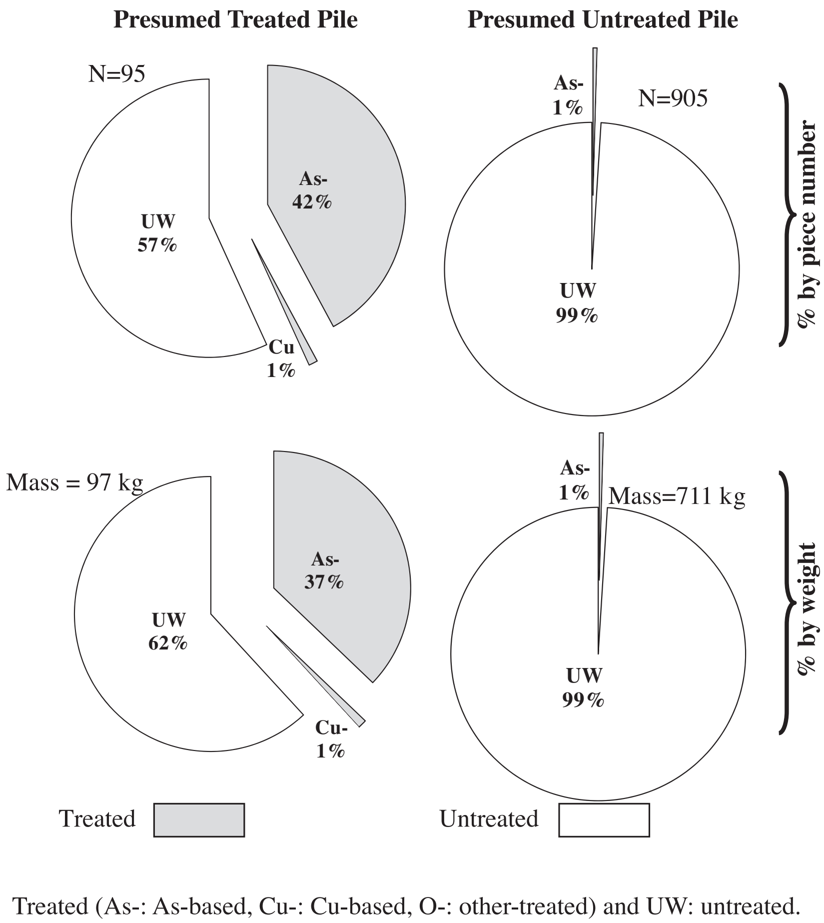

Fig. 6. Wood distributions in presumed treated and presumed untreated piles after an experiment conducted using a 95:05 wood infeed. Experimental parameters included a belt speed of 0.5 m/s and a feeding rate of 60 pieces per min. Wood distribution is based on number of pieces (above) and weight (below).

a sacrifice is generally made to incorrectly divert at least one untreated piece for every piece of treated wood in the infeed. This loss of untreated wood to the presumed treated pile represents a relatively small fraction (about 2.5% of UW in the infeed) of all wood diverted; the majority of the wood was diverted correctly.

4.3.2. UP composition

The presumed untreated pile is the most important pile for wood recycling facilities since it represents their infeed for recycling. For the 50:50 experiments, 78–86% and 76–88% of the piles were UW, by number and weight, respectively. Almost, another 10% by number and weight were Cu- and O-treated pieces. In the 95:05 experiments, the presumed untreated pile was composed of 98–99% of UW by number and weight (Fig. 6). So, as the treated wood fraction increased (5–50%) in the infeed, the fraction of treated wood will increase in the wood recycle stream. Thus, maintaining a wood infeed of high quality is critical for assuring an optimal recycled product as observed through the composition of the UP.

5. Environmental impact

To evaluate the implications of this research, two cases are discussed. The first case focuses on recycling the recovered wood waste as mulch. Some of the states in the U.S. and other countries in the world have adopted risk-based clean soil thresholds that are often used as a first cut assessment of whether a waste can be land applied or not. In Florida, land applied materials should meet the soil clean-up target levels (SCTL), and these are generally lower for the arsenic by roughly a factor of 100 relative to copper and chromium, and thus arsenic is the most stringent criteria that will typically govern the design of a particular wood sorting system. The specific arsenic guideline level for land application of materials in residential areas is 2.1 mg As/kg of the soil-applied material such as mulch, and 12 mg/kg for commercial and industrial applications (FDEP, 2005). Florida SCTL is considered strict when compared to other states in the U.S. The 95:05 infeed used in this study had 166 mg As/kg of wood (assuming the As concentration in the UW as 0.05 mg As/kg wood, Hasan, 2009). With the XRF sorting system used in the current study, the presumed untreated pile had reduced arsenic levels of 1.80 mg/kg (for BS = 0.5 m/s, and FR = 20 pc/min), which were within the residential SCTLs, in addition to 4.40 mg/kg (for BS = 0.375 m/s, and FR = 20 pc/min), and 8.40 mg/kg (for BS = 0.5 m/s, and FR = 60 pc/min) which were within the commercial SCTLs. Chromium and Cu residential SCTL criteria, which are less strict than As, were met in all four experiments of the 95:05 infeed set. Thus, the technology achieved considerable improvements in the quality of the wood that could ultimately be used for recycling purposes; however, additional improvements are needed to the system to make sure that the strict 2.1 mg/kg level needed for residential applications is achievable at all times during the operation of the system. Improvements can be achieved through the redesign of the wood conveyance system which will minimize the tendency for wood to bounce when sorted into treated versus untreated wood piles.

The second case addresses the recycle as wood fuel. C&D wood can be used as fuel in cogeneration plants with the assumption that the resultant ash can be disposed in landfills. The USEPA requires that all hazardous materials that fail the toxicity characteristic leaching procedure (TCLP) (US EPA, 1992) to be disposed in lined landfills. Solo-Gabriele et al. (2002) showed that C&D wood should contain less than 5% TW by number, in order to pass the As-criterion. In this research, the 95:05 pile (real case situation without sorting) lies on the limit of this criterion, and with sorting the TW% was reduced down to levels that would pass the As-criterion of the TCLP (0.77–1.70% for TW and 0.33–1.12% for As-based pieces). The 50:50 pile (the balance case) did not meet the criteria even with sorting that resulted in mass recoveries as high as 95%. The best way to improve the quality of a 50:50 pile would be to augment XRF detection and sorting with visual practices as this will help to reduce the contamination prior to the automated detection and sorting.

In the future, As-treated wood will decrease in the waste stream due to phase-out, and Cu-treated will most probably increase. Copper has much less stringent criteria than As, but the percentage of Cu-treated wood in the C&D waste stream might increase significantly, because its actual useful life is less than the As-treated wood (Freeman and McIntyre, 2008; Hasan, 2009). Hence, copper might exceed the SCTL for both mulch and ash intended as soil supplement. Proper and efficient wood sorting is also needed for this future consideration. An XRF based sorting system would be an attractive option to divert Cu in waste wood from the recycled stream.

6. Conclusions and recommendations

The main purpose of sorting wood at recycling facilities is to decrease the contamination in the recycled stream, as represented by the presumed untreated pile in this research, and to divert the contaminated pieces in the presumed treated pile into more acceptable disposal options such as lined landfills. This can be accomplished by enhancing both the treated and untreated wood sorting efficiencies. Treated wood detection efficiency was shown previously in Part I of this two paper series to depend on the XRF-detection system parameters with mass recovery efficiencies of 98%, 91%, and 97% for As, Cu, and Cr, respectively. Sorting efficiencies for these three metals were a function of infeed composition with mass recovery dropping to 96.7, 83.4, and 95.2 for the 50:50 infeed and 93.3, 87.7, and 92.6 for the 95:05 infeed. Comparison of these two data sets suggests that about one-half of the errors in sorting were due to detection and the other half due to conveyance.

Enhancing the conveyance, and especially for the untreated wood, required decreasing the overlapping and bouncing events. The optimum results were obtained at the lowest feeding rate of 20 pc/min and the highest BS of 0.5 m/s with feeding rate playing a larger role in the performance of the system. The lowest feeding rate decreased the overlapping events and the highest BS decreased both the overlapping and bouncing.

Overlapping of untreated wood with treated wood can be decreased by training the wood pickers ahead of the system to practice visual sorting and to feed only the suspected pieces to the system. This will decrease both the number of treated pieces fed to the system and the feeding rate.

Bouncing of wood can be decreased by replacing the inclined conveyor with low height horizontal roller conveyor, and increasing the height of the shielding between the two presumed piles, in addition to operating the system at the highest belt speed. Another alternative that can be considered to minimize bouncing effects is homogenizing the wood infeed by adding a wood chipper upstream. Though this option would result in increasing the investment, operational, and maintenance costs of the sorting process, it deserves to be studied on the basis of enhancing the quality of recycled materials. Sorting uniform pieces of wood will minimize the conveyance and diversion problems associated with handling such large differences in wood size; however, this improvement in uniformity of the infeed will require very rapid detection due to the larger number of smaller pieces of wood that would need to be sorted. One recommendation for future work is to evaluate whether size reduction of the wood infeed will enhance overall sorting efficiencies. This is especially relevant for large wood cogeneration facilities which receive size reduced wood as their infeed. If the efficiencies are good, sorting of size reduced wood may represent one additional option for wood cogeneration facilities, to assure that their wood infeed is free of metal contaminants.

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