Gypsum and organic matter distribution in a mixed construction and demolition waste sorting process and their possible removal from outputs

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ABSTRACT

With insufficient source separation, construction and demolition (C&D) waste becomes a mixed material that is difficult to recycle. Treatment of mixed C&D waste generates residue that contains gypsum and organic matter and poses a risk of H_2S formation in landfills. Therefore, removing gypsum and organic matter from the residue is vital. This study investigated the distribution of gypsum and organic matter in a sorting process. Heavy liquid separation was used to determine the density ranges in which gypsum and organic matter were most concentrated. The fine residue that was separated before shredding accounted for 27.9% of the waste mass and contained the greatest quantity of gypsum; therefore, most of the gypsum (52.4%) was distributed in this fraction. When this fine fraction was subjected to heavy liquid separation, 93% of the gypsum was concentrated in the density range of 1.59–2.28, which contained 24% of the total waste mass. Therefore, removing this density range after segregating fine particles should reduce the amount of gypsum sent to landfills. Organic matter tends to float as density increases; nevertheless, separation at 1.0 density could be more efficient.

1. Introduction

With insufficient source separation, construction and demolition (C&D) waste becomes a mixed material that is difficult to recycle. The Japanese Ministry of Land, Infrastructure, Transport and Tourism [1] reported that 2.9 Mt of mixed C&D waste were generated in Japan in 2005. Fig. 1 shows the mass flow of mixed C&D waste in 2005. Nearly 1.6 Mt were directly landfilled, and the remaining 1.3 Mt were delivered to treatment facilities where 0.43 Mt were recovered, 0.37 Mt were reduced, and 0.5 Mt became residue that was landfilled. However, disposal of such residue has become a serious issue because it still contains various substances such as organic matter (paper and wood), drywall (made mainly of paper liner and gypsum: $CaSO_4 \cdot 2H_2O$), ferrous metals, and other heavy metals [2,3] and is regarded as the major contributor of hydrogen sulfide (H_2S) generation in landfills.

The activity of sulfur-reducing bacteria generates H_2S in landfills. Many recent studies have indicated that the gypsum and organic substances contained in C&D waste are major sources of sulfates and organic substrates and thereby increase H_2S levels. Lee et al. [4] collected numerous gas samples from ten C&D debris landfills in Florida and detected H_2S at all sites. Townsend et al.

[5] used column experiments to study the leachate of mixed C&D waste and identified high sulfate concentrations resulting from gypsum drywall. Jang and Townsend [6] also found that large amounts of sulfate leached out from C&D debris fines because of gypsum particles. Plaza et al. [7] reported that H_2S concentrations ranged from 50,000 to 150,000 ppm in their column experiment involving packed gypsum drywall. Inoue [8] examined the potential for H_2S formation from various gypsum boards and residues of mixed C&D waste sorting and identified a relationship between H_2S-generation and ignition loss (IL) of samples. On the basis of Inoue's study [8], in 2005, the Japanese government established criteria (IL < 5%) for C&D waste residue sent to inert-waste landfills. Residue not meeting these criteria must be sent to landfills for non-hazardous waste. As disposal in landfills for non-hazardous waste is twice more expensive than in those for inert waste [9], industries involved in mixed C&D waste disposal are incurring sizeable expenses.

To reduce the quantities of gypsum and organic matter sent from sorting processes to landfills, we must first clarify how these components are distributed throughout the sorting process, how they accumulate in certain parts of the process, and how they can be removed from the waste fraction sent to landfills. Therefore, the first objective of this study was to identify which outputs contained the most gypsum and organic matter. A batch experiment conducted at a real sorting facility investigated gypsum and organic matter distributions in the sorting process. The second

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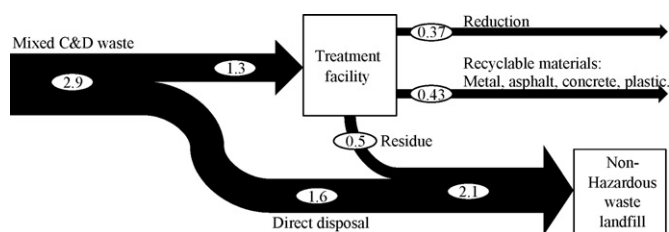 E-mail address: amontero@eng.hokudai.ac.jp (A. Montero).

Fig. 1. Mass flow of mixed construction and demolition (C&D) waste in 2005 in Japan (unit: Mt/year) (Ministry of Land, Infrastructure and transport, Japan).

objective was to explore possible ways to remove gypsum and organic matter from the outputs identified by the first objective. Of particular focus was density separation. Hence, we investigated the density ranges in which most of these substances were concentrated.

Furthermore, the relationship between gypsum content and IL is discussed because the presence of much gypsum in residue can influence IL. Gypsum ($CaSO_4 \cdot 2H_2O$) loses its crystallized water by heating and is gradually converted to hemihydrate ($CaSO_4 \cdot 1/2H_2O$) and anhydrite ($CaSO_4$). Although the transformation temperature depends on various factors [10], past studies have reported conversion to hemihydrate between 100 and 200 °C, γ-$CaSO_4$ formation with heating above 250 °C, and β-$CaSO_4$ with further heating to around 360 °C [11,12]. Even at temperatures below 70 °C, very slow conversion to hemihydrate has been observed [11]. Therefore, at 600 °C, dehydration of gypsum may affect IL.

2. Methodology

2.1. Treatment process

The investigation was conducted at a treatment facility that accepts typical mixed C&D waste in the Tokyo area. This facility receives almost 1000 m³ of C&D waste every day. After large-sized recyclables such as iron frames, reinforcing bars, wood panels, recyclable plastics, and drywall are removed manually or by heavy equipment, the remaining material, accounting for nearly 23% of the initial volume, is then subjected to the sorting process shown in Fig. 2. First, the mixed C&D waste (Input) is treated using a 30-mm screen. Any particles smaller than 30 mm are sent to a magnetic separator (Metal A), and the fine fraction (<8A) is separated using an 8-mm screen. The remainder (8–30 mm in size) is segregated by an air classifier into light and heavy fractions (Heavy A). The light fraction is again put into the line at the shredder point; this process is denoted as the Non-shredded Line (A).

Particles larger than 30 mm (removed by the first screen) go to a hand-sorting operation where recyclables such as metal, wood, paper, plastic, and concrete are removed (Recyclable). The remainder is then subjected to a high-speed shredder. The process after this point is denoted as the Shredded Line (B). The shredded material goes to a trommel where particles larger than 100 mm (>100) are removed. Of the particles smaller than 100 mm, the fine fraction is first removed using an 8-mm screen (<8B). Particles 8–100 mm in size are then treated using a 30-mm screen, separating them into 8–30 mm and 30–100 mm fractions. Particles smaller than 30 mm are further separated using an air classifier into heavy (Heavy B) and light (Light) particles. A magnetic separator (Metal B) follows the hand-separation process. Metal A, Metal B, and Recyclables are all recycled; Heavy A and Heavy B are recycled as aggregates; <8A and <8B are sent to landfills; and >100, 30–100, and Light are sent to an incinerator or used as alternative fuel, depending on their quality.

2.2. Batch experiment procedure

A total of 1740 kg (3.22 m³) of mixed C&D waste was prepared for the experiment; this mixture was selected by facility personnel as approximately typical waste in the sorting process. All the waste went through the sorting process, after which the outputs were weighed. Immediately after, 5–10 kg samples for analysis were obtained from <8A and <8B, Heavy A and Heavy B, Light, >100, and 30–100 using the cone and quarter sampling method [13,14]. Ferrous metals from both lines and recyclables separated by hand-sorting were weighed but not sampled because they generally have known components and are recycled.

In addition to this batch experiment, five outputs (<8A and <8B, Heavy A and Heavy B, and Light) were sampled periodically during regular operation of the facility to investigate fluctuations in output characteristics. This sampling took place over 3 days for about 2 h every day. Samples from five outputs were obtained 7–8 times within 2 h at 15-min intervals. In total, 21 samples of 3–5 kg were obtained from each output within a 3-day period.

2.3. Analytical methods

Each of the seven samples obtained during the batch experiment was analyzed for the following: water content (WC), physical composition, solid total organic carbon (TOC), gypsum content, and IL. Each sample was dried at 105 °C for 24 h before analysis (except for analyses of WC and gypsum content). Analyses of WC, physical composition, and IL were based on Directive No. 95 from the Ministry of Health and Welfare of Japan [15].

Water content (WC): a 10-g sample of the original sample (W_0) was dried at 105 °C for 24 h (W_1), and WC was then calculated as $WC = (W_0 - W_1)W_0^{-1}$. Although slow dehydration of gypsum is possible in drying at 105 °C, this procedure followed that given in the Directive.

Physical composition: two hundred and fifty grams of dry sample (W_t) was sieved through a 2-mm screen. Particles larger than 2 mm were visually classified as concrete, drywall-like material, metal, glass, wood, paper, and plastic. Particles smaller than 2 mm were classified simply as <2 mm. The fractions were weighted (W_i) and ratios were calculated as $PF_i = W_i W_t^{-1}$.

TOC: dry sample was shredded and 0.5 g was analyzed using a TOC analyzer (Shimadzu TOC-V SSM-5000A). Particles of 30–100 mm and >100 mm were not analyzed because these were too large to be homogenized.

Gypsum determination: Porta [16] reviewed several methodologies for analyzing gypsum in soil. Of these, this study used the electroconductimetric determination of gypsum by Richards [17]. The detailed procedure is not described here. However, the liquid-to-solid ratio was set at a higher level than in Richards's [17] original method because the gypsum content was expected to be higher. A preliminary experiment indicated that a solid-to-liquid ratio of at least 1:100 was necessary for the samples analyzed in this study.

IL: ten grams of dry sample (W_1) was ignited at 600 °C for 3 h (W_2), and IL was calculated as $IL = (W_1 - W_2)W_1^{-1}$.

Samples obtained by periodic sampling were analyzed for WC, IL, TOC, and weight loss at 200 °C using the analytical methods described above. The method for analyzing weight loss at 200 °C was identical to the IL procedure except for the temperature. Weight loss at 200 °C was analyzed to determine the approximate amount of crystallized H_2O in each sample because major weight loss associated with dehydration has been reported to occur up to 200 °C. Although dehydration is not necessarily complete at 200 °C, weight could be reduced by nearly 15% if dihydrate is converted to hemihydrate [11,12].
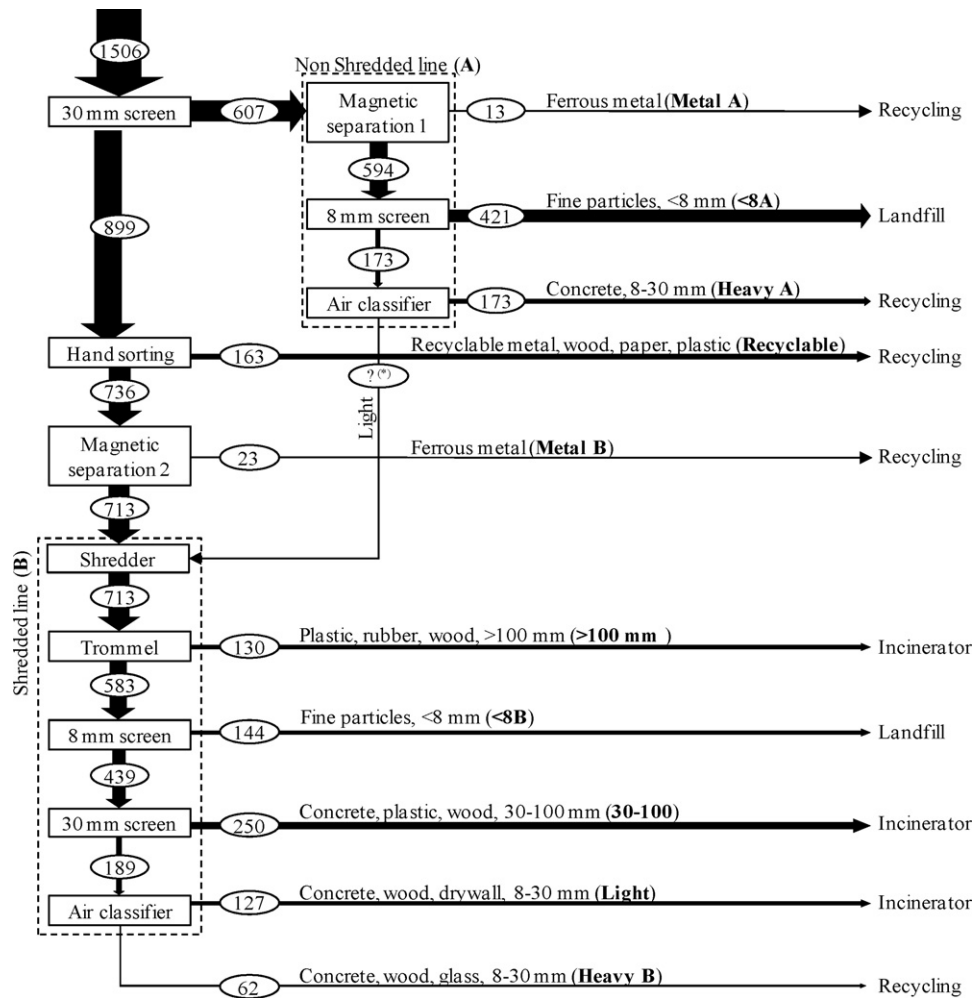
Fig. 2. Sorting process at the investigated treatment facility and the mass flow obtained from the batch experiment (unit: kg). The numbers in the figure indicate the corresponding value of the flow, where 1506 kg was collected (86.6% recovery rate). *The amount of material was not measured for this Light fraction.

2.4. Heavy liquid separation procedure

As shown in Table 1, drywall has a relatively low density because it has pores [18,19]. In contrast, pure gypsum crystals have a density of 2.4 g cm^{-3}. Therefore, one can determine whether gypsum appears as drywall or fine particles by identifying the density range in which the gypsum is concentrated. If this can be achieved, it may also be possible to separate gypsum from other materials.

The five output samples (<8A and <8B, Heavy A and Heavy B, and Light) were separated by the heavy liquid procedure using the following liquid densities: distilled water for a density of 1.0 g cm^{-3}, $CaCl_2$ for densities of 1.1–1.3, $Ca(NO_3)_2$ for densities of 1.4–1.5, CCl_4 for densities of 1.59, CH_2BrCl for densities of 1.92, and CH_3I for densities of 2.28. Because gypsum is water-soluble, calcium solutions

were mainly used to prevent the gypsum from dissolving during the procedure [20–23]. For the procedure, 40 g of sample was placed into 400 ml of a heavy liquid and shaken for 10 min at 150 rpm; particles with a density lower than the liquid floated, while the others sank. The float and sink were separated and analyzed for gypsum and TOC using the methods described in Section 2.3.

3. Results and discussion

3.1. Mass distribution of the batch experiment

A total of 1506.44 kg was collected for a total recovery rate of 86%. Based on discussions with facility personnel, loss was assumed to have resulted from loss as dust, small particles falling from the conveyor belt, and evaporation during processing. Fig. 2, drawn based on the collected amount, shows the mass flow of the batch experiment.

The results indicated that <8A accounted for 27.9 (obtained by dividing 421 kg by 1506 kg. The following percentages were calculated in the same way) and <8B accounted for 9.6% of the total mass. Thus 37.5% of the total output was composed of fine particles that required disposal. With regard to recyclables, 2.4% of the total mass was recovered as ferrous metals, 15.6% as aggregates, and 10.8% by manual separation. A relatively large quantity of materials was to be sent for incineration: in total, >100, 30–100, and Light accounted for 33.6% of the total mass.

Table 1
Densities of some materials contained in construction and demolition waste [19].

Material	Density (g cm^{-3})
Drywall	0.72–1.0[a]
Gypsum ($CaSO_4 \cdot 2H_2O$)	2.3
Rubber	0.91–2.0
Wood	0.35–0.9
Paper	0.25–1.52
Glass	2.0–2.6
Plastic	0.91–2.3
Fe	7.87

[a] Gypsum Association, 2005; Steel Built, 2008.

Table 2
Physical composition of each output during the batch experiment.

Output	Material (%)						
	Concrete	Walls	Metals	Glass	Wood	Paper/plastic	<2 mm
<8A	14.5	2.9	0.0	0.5	1.3	1.3	79.6
Heavy A	77.8	6.7	0.0	6.7	2.0	1.1	5.7
<8B	16.0	1.0	0.2	1.8	1.8	1.4	77.9
Heavy B	74.3	8.8	3.6	7.2	2.9	1.4	1.7
Light	51.7	9.3	0.1	5.9	4.4	8.9	19.7
30–100	34.2	11.6	2.0	1.1	12.2	36.1	2.7
>100	0.0	3.8	3.3	0.0	10.6	80.4	2.0

3.2. Physical composition

Table 2 shows the physical composition of each output. Both fine fractions (<8A and <8B) had a similar composition: nearly 80% particles smaller than 2 mm and 14–16% concrete. Both heavy fractions were also very similar, mostly composed of concrete. Large fractions (e.g., >100 and 30–100) contained large quantities of paper, wood, and plastics, as intended by the sorting-process design. Drywall-like material (Walls) was identified in each fraction of both lines, mainly in Light (9.3%), Heavy A and Heavy B (6–9%), and 30–100 (7.9%). However, we could not confirm that this material was definitely drywall.

3.3. Ignition loss, total organic carbon, and gypsum content

Fig. 3 shows the results of IL, TOC, and gypsum content for each output; quantities represent the average results of duplicate samples. With the exception of Heavy, samples from both lines had IL values far greater than the acceptable level of 5%. The influence of crystallized water in gypsum on IL is discussed in Section 3.4.

The samples of <8A and <8B contained the highest concentrations of gypsum. Musson et al. [2] reported that fine C&D debris obtained from American facilities contained 1–25% gypsum by mass. Results for <8A and <8B were within that range. Heavy A, Heavy B, and Light also had relatively high gypsum contents. Large fractions such as 30–100 and >100 contained low levels of gypsum, possibly because fine particles attached to larger components.

TOC is thought to be a better indicator of organic content than IL, although the two measures cannot be directly compared. In <8A and <8B, TOC slightly exceeded 5%. As TOC indicates only organic carbon content, the total content of organic matter must be much higher.
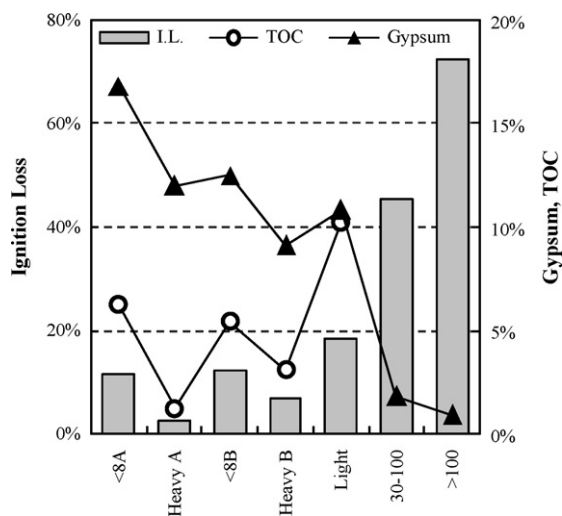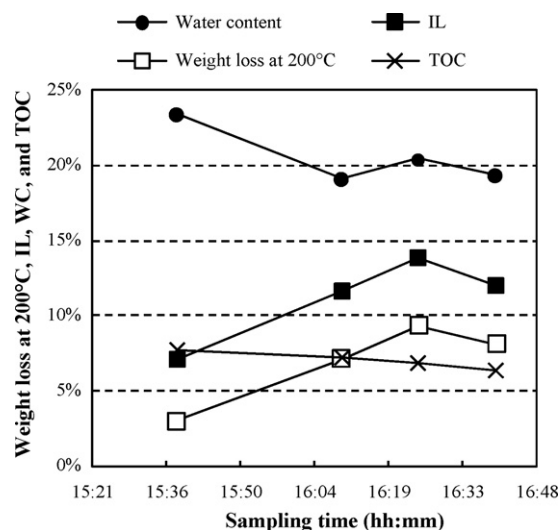

Fig. 4. Fluctuation of weight loss at 200 °C, ignition loss (IL), water content (WC), and total organic carbon (TOC) for the <8A sample obtained by periodic sampling.

Therefore, based on the TOC results, this fine matter probably does not meet the Japanese government's IL criterion (IL < 5%) mentioned in the introduction.

3.4. Fluctuations in the output characteristics

Fig. 4 shows fluctuations in IL, WC, weight loss at 200 °C, and TOC for four <8A samples obtained by periodic sampling on 30 August 2007. Weight loss at 200 °C became high when IL was high. Fig. 5 shows all data for IL and weight loss at 200 °C for <8A and <8B obtained by periodic sampling. A correlation coefficient of $R^2 = 0.6219$ was calculated for these data. A significance test indicated that this R is statistically significant under the significance level ($\alpha = 0.01$). Thus the IL results for <8A in the batch experiment were to some extent affected by crystallized water in gypsum. Although more in-depth investigation is necessary, IL cannot simply be used as an index of organic content for samples containing much gypsum such as <8A. If IL is used as an index of organic matter, then the influence of weight loss caused by crystallized water should be removed before determining IL.
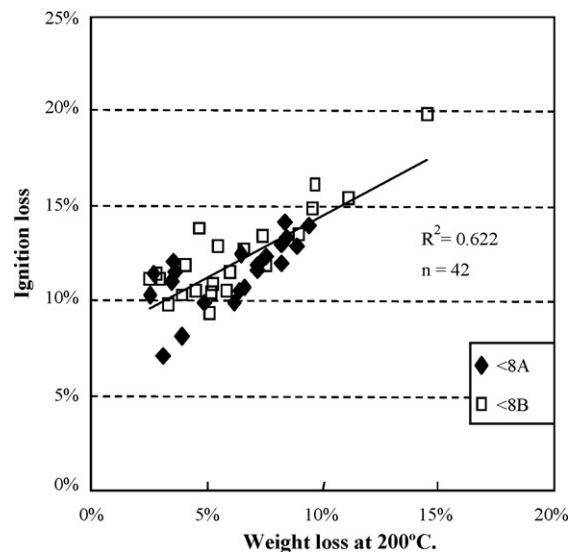

Fig. 3. Ignition loss (IL), total organic carbon (TOC), and gypsum content of each output obtained during the batch experiment.

Fig. 5. Correlation between weight loss at 200 °C and ignition loss (IL) for the <8A and <8B samples obtained by periodic sampling.
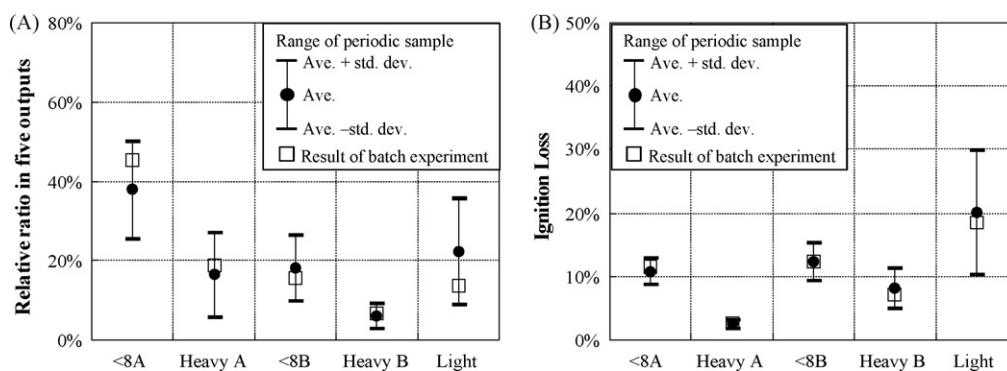
Fig. 6. Comparison of the mass distribution ratios and ignition losses from the batch sample and periodic sampling.

Next, the characteristics of the batch and periodic samplings were compared. Ideally, comparison should be done based on every output. However, in the periodic sampling, samples could only be collected from five outputs because of the difficulty of sampling during regular operation of the facility. Hence, here, the distribution ratios and characteristics of five outputs obtained by the batch experiment and periodic sampling were compared. Fig. 6 presents the mass distribution ratio, calculated by setting the sum of five outputs as 100%. For periodic samples, the average and range of standard deviation of 21 samples are indicated. Fig. 6A shows that the ratio of each output obtained by the batch experiment was within the range of standard deviation of the periodic sampling. Fig. 6B gives the range of IL obtained by periodic sampling, showing that the results obtained in the batch experiment are close to the average of periodic sampling. These results indicate that even though waste inputs fluctuate, batch samples can represent the waste treated in this facility.

3.5. Material distribution during the sorting process

The distribution ratios of gypsum and organic matter were calculated by dividing the amounts of gypsum and organic matter transferred to each output by the total amount recovered. For this, the amounts of gypsum and organic matter transferred to each output were determined by multiplying the results of the analysis for each output and the mass of each output. The best choice for organic matter would be a measurement of organic carbon content, such as TOC. However, analyzing TOC levels for 30–100 and >100 was not possible because of their size; therefore, IL was used as a substitute.

Table 3 presents the mass, gypsum, and IL distributions of the process; about half of all gypsum (52.4%) was distributed to <8A, and another 13.4% was distributed to <8B. Therefore, 65.8% of all gypsum was distributed in fine matter with particles smaller

Table 3
Gypsum and ignition loss (IL) distributions of the process based on samples obtained during the batch experiment.

Output	Mass distributions	Gypsum distributions	IL distributions
<8A	27.9%	52.4%	15.4%
Heavy A	11.5%	15.4%	1.3%
Metal A	0.9%	–	–
<8B	9.6%	13.4%	6.0%
Heavy B	4.1%	4.2%	1.4%
Light	8.4%	10.2%	7.1%
30–100	16.6%	3.4%	37.3%
>100	8.6%	0.9%	31.4%
Metal B	1.5%	–	–
Recyclables	10.8%	–	–
Total	100%	100%	100%

than 8 mm, which is sent to landfills. Gypsum distributed to <8B accounted for 41.7% of all gypsum that entered the shredding process (Line B). Of the remaining gypsum, 19.6% was distributed to Heavy A and Heavy B, which are recycled as aggregate, and 14.5% was distributed to large size fractions, which are thermally treated.

These results indicate that the gypsum in mixed C&D waste tends to be concentrated in the fine fraction. Also, 67.8% of all gypsum was separated into Line A, i.e., by the first screen. Thus, at delivery, more than half of all the gypsum in mixed C&D waste is composed of particles smaller than 30 mm. Therefore, segregating the fine fraction using an appropriate screen at the beginning of the process will be an effective measure for separating gypsum from mixed C&D waste. However, final disposal still requires removing gypsum from the segregated fine fraction.

As mentioned above, crystallized water in gypsum affects IL. However, if IL can be assumed to be a sufficient indicator of organic matter, then 68.7% of all organic matter appears to have been distributed within the fraction of large components such as 30–100 and >100.

Thus from the perspective of managing gypsum and organic matter, the <8A fraction is crucial because it accounts for 27.9% of the mass and contains the highest concentration of gypsum; it is the main destination of gypsum throughout the process and has high IL values exceeding criteria.

3.6. Density range identification

The following sections discuss the results of density range identification conducted for <8A. First, mass distributions of float and sink were determined using various heavy liquids, as shown in Fig. 7A. For each heavy liquid, mass distribution was calculated by dividing the amount of float/sink mass by the sum of both. The recovery rate for each heavy liquid density, representing the ratio of recovered mass to total amount of mass used, was between 96.7% and 99%. As shown in Fig. 7A, 33% of the mass floated at a liquid density of $1.5\,g\,cm^{-3}$, and this fraction increased gradually as the liquid density increased up to 2.28.

Fig. 7B shows the gypsum distribution for the <8A sample. The lowest recovery rate was 97.9% at density 1.0, mainly because some gypsum dissolved in pure water. As the liquid density increased, a recovery rate of almost 100% was possible because heavy liquids containing Ca reduced gypsum dissolution [20–23]. Although almost all gypsum sank until a liquid density of 1.59, a marked shift to float occurred at densities above 1.92. As shown in Table 1, the density of drywall is 0.72–1.0 and that of gypsum crystals is 2.3. Therefore, the results of heavy liquid separation indicated that the gypsum contained in <8A was composed of fine particles of gypsum crystal rather than drywall. Specifically, 93% of the gypsum had a density between 1.59 and $2.28\,g\,cm^{-3}$ (calculated from Fig. 7B by
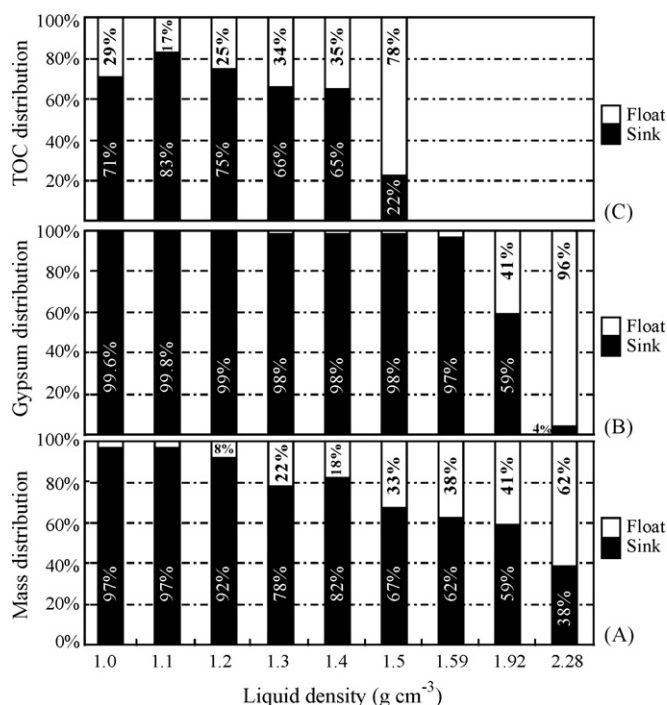
Fig. 7. Mass distribution, gypsum distribution, and TOC distribution for the <8A sample after heavy liquid separation.

subtracting the percentage of sunk gypsum at a density of 1.59 from the percentage of sunk gypsum at 2.28, i.e., 97–4%). Based on the mass distribution indicated in Fig. 7A, the mass contained in the same density range was 24% of the total sample mass (calculated by subtracting the percentage of sunk mass at a density of 1.59 from the percentage of sunk mass at 2.28, i.e., 62–38%); that is, output <8A yielded 24% of the sample mass, containing 93% of the total amount of gypsum.

From the above findings, the following separation process is proposed to separate gypsum from <8A. First, separating at density of 1.59 should allow for collection of the fraction heavier than 1.59. Next, from this heavy fraction, the light fraction should be separated at density of 2.28; this light fraction contains 93% of the total gypsum initially contained in <8A and its gypsum content will become 65.8%. Other separated fractions such as those lighter than 1.59 and heavier than 2.28 will have gypsum contents of 1.33% and 1.78%, respectively. Hence, by applying this separation, three fractions can be obtained: gypsum concentrate accounting for 24% of the initial mass, and light and heavy fractions, which contain little gypsum, together accounting for 38% of the initial mass.

Fig. 7C shows the TOC distribution after heavy liquid separation of <8A from densities of 1.0–1.5 g cm^{-3}. A higher density than 1.5 is not indicated because of using an organic solvent. The minimum recovery rate for densities from 1.0 to 1.5 was 80%. These experiments indicated that 78% of TOC in sample <8A had a density of 1.5 g cm^{-3} or less. However, separation at density of 1.5 would not be so efficient in terms of TOC concentrate because TOC would be 14.2% if 78% of the organic carbon were transferred to 33% of mass. However, separation at density of 1.0 would produce concentrate with 58% TOC in 3% of the total mass.

4. Conclusions

A batch experiment was conducted to investigate distributions of gypsum and organic matter in a sorting process at a real facility. Furthermore, to suggest possible ways of removing gypsum and organic matter, heavy liquid separation was performed, examining

density ranges in which gypsum and organic matter were most concentrated.

The following are the major conclusions:

(a) In the batch experiment, outputs <8A and <8B had the highest mass distributions (27.9 and 9.6%, respectively). Therefore, nearly 40% of the total mass was in the fine fraction requiring disposal.
(b) In the batch experiment, 52.4% and 13.4% of the total collected gypsum came out of outputs <8A and <8B, respectively. This indicates that collected gypsum was originally fine or was reduced from its original drywall form to fine material during the process.
(c) Organic matter was distributed mainly in fractions composed of large-sized components. However, a considerable amount of organic matter was also fine matter requiring disposal.
(d) Analysis of the fine fraction by heavy liquid separation indicated that 93% of the gypsum was concentrated in the density range of 1.59–2.28 g cm^{-3}, which contained 24% of the total mass.
(e) Organic matter was mainly contained in densities below 1.5.
(f) The above findings indicate that since gypsum is mainly distributed in the fine fraction and has a high density, the amount of gypsum going to landfills can be reduced by first separating the fine fraction from mixed C&D waste and then removing particles in the density range of 1.59–2.28 g cm^{-3}. These measures could remove 24% of the mass, containing 93% of the gypsum, resulting in a gypsum concentration of only 15.54 g kg^{-1} in residual fine matter.

The main contribution of this research is that it determined the density range in which gypsum is mainly found in the residue of the sorting process. If this density range could be removed, the amount of gypsum remaining in the spare output would be drastically reduced, thereby reducing the H_2S-generation risk in landfills and providing both economic benefits for the treatment industry and enhancing the safety of landfill workers.

This study conducted heavy liquid separation only to determine the density range in which gypsum/organic matter was concentrated. This inevitably required a wet process and use of hazardous chemicals. In practical applications, however, a dry separation process that can produce separation at this high-density range would be preferable. Also, further investigations at other facilities are necessary to obtain more universal data.

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