Undesirable Substances Reduction in Solid Fuel Recovered from Municipal Solid Waste of Russia

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Abstract. There has been substantiated the approach to high quality SRF production from MSW based on the analysis of waste chemical and morphological composition. The method involves analysis of undesirable elements content in MSW morphological components and targeted removal of the components that are predominant carriers of the undesirable elements. The morphological components to be removed has been identified, the physical attributes of their distinction from target fuel components have been chosen, the methods of separation and related equipment have been proposed. The application of the proposed combination of methods to the MSW of Russia has been modelled with a favourable outcome on all relevant heavy metals and chlorine.

1. Introduction

The production of solid recovered fuel (SRF) from municipal solid waste (MSW) is currently one of the most promising way to process waste. SRF has found wide application in cement plants as additional fuel for cement clinker production thereby providing carbon emission and cost reduction. A solid fuel contains numerous substances and impurities that, after combustion in a cement kiln, are included to cement clinker, thus, having negative impact on both the process and the product. The main problem in the production of fuel from MSW is to decrease the concentrations of undesirable substances to permissible limits with the maximum content of a caloric component.

As was shown in [1], the addition of the compounds of different elements with fuel can influence the process of cement production in the following manners:

a) The element is included in the composition of cement clinker. The conditions of CaO binding, which are responsible for the constructional performance properties and quality of cement, are changed. The elements and compounds that exert this effect will be referred to as technologically important ones.

b) Toxic substances are formed as environmental pollutants.

c) The intensity of equipment deterioration and kiln lining erosion and the consumption of resources can change. The elements of this category are not considered separately because they are traditionally regulated within the framework of the above two groups.

This work is dedicated to developing an approach to this problem followed by specific technological recommendations for modern MSW of Russia. The approach is based on a material flow analysis that is widely used in MSW processing studies [2, 3, 4]. Particular mention should be made to the study [5], who used this method for refuse derived fuel production processes. Unfortunately, the research does not address the current practical task of modern MSW processing, as it was based on 15 years-old
MSW composition and did not include analysis of a comprehensive list of modern separation methods.

2. Materials and methods
It is impossible to recommend particular maximum permissible concentrations of the technologically important elements in fuel ash because these limits depend on charge mixture composition and the requirements imposed on clinker composition at a particular plant. The fuel from MSW cannot be considered as a source of the addition of the required amounts of technologically important elements because of the instability of initial MSW composition. Thus, in SRF production, the task can be described as follows [1]:

– to purposefully decrease the concentrations in the fuel of all elements whose possible supply with ash is a considerable fraction of their permissible concentrations in clinker (Cr, Na, S, P);

– to exclude the unforeseen supply of large SiO2 amounts related to the fluctuations of the ash content of the initial MSW by purposeful extraction of high ash morphological components from the fuel.

Then, the chemical composition of clinker can be adjusted by means of raw mill composition only, whose components are predictable and stable.

As for toxic substances, there are particular limits of their permissible concentrations in fuel; correspondingly, the required characteristics of the efficiency of waste separation can be calculated [6]. The approach to the problem of solid refused fuel quality is detecting the MSW morphological components that are the sources of undesirable chemical elements and using operations specially directed toward the extraction of these components. The approach was substantiated by means of material flow analysis.

The following data were used:

– the summary results of the long-standing full-scale observations of the morphological composition of mixed MSW in St. Petersburg, with consideration of the research [7] (the modal values of the concentrations of morphological components are presented in Table 1(a) and Table 1(b)).

– the data on the concentrations of potentially problematic chemical elements in different morphological components of MSW obtained by foreign researchers [5, 8, 9]. The following data (modal values) on the chosen morphological components are available: low heat value, ash content on a dry weight basis, moisture content, and the concentrations of sulfur, aluminum, phosphorus, sodium, iron, magnesium, chlorine, arsenic, cadmium, chromium, copper, mercury, nickel, lead, and zinc on a dry weight basis.

### Table 1(a). MSW morphological composition [1].

| Morphological component | Total, % |
|-------------------------|---------|
| Paper and cardboard     | 18.00   |
| Food waste              | 18.00   |
| Garden waste            | 3.20    |
| Glass                   | 11.00   |
| Stone                   | 0.72    |
| Metal (nonferrous)      | 0.76    |
| Metal (ferrous)         | 4.00    |
| Polymers (PET bottles, polyethylene, and polypropylene) | 10.00 |
| Polymers (others)       | 3.00    |
| Batteries               | 0.07    |
| Electronics             | 0.34    |
| Leather, rubber, and footwear | 0.48 |
| Textiles                | 6.50    |
| Wood                    | 2.50    |
| Ceramics                | 0.86    |

### Table 1(b). MSW morphological composition.
The addition of the $i$ th element with the $j$ th morphological component of MSW (% on a total element basis) was calculated by formula:

$$x_j = \frac{\alpha_{iw}^i}{\alpha_{w}^i} \alpha_j = \frac{\alpha_{dw}^i (1 - W_j)}{\alpha_{d}^i (1 - W_j)} \alpha_j,$$

(1)

where $\alpha_{iw}^i, \alpha_{dw}^i$ are the concentrations of the $i$ th element in the $j$ th morphological component of MSW on a wet and dry weight basis, respectively, mg/kg; $\alpha_{w}^i, \alpha_{d}^i$ are the total concentrations of the $i$ th element in MSW on a wet and dry weight basis, respectively, mg/kg; $\alpha_j$ is the concentration of the $j$ th morphological component of MSW with consideration for moisture, %; $W_j$ is the moisture content of the $j$ th morphological component of MSW, %; and $W$ the moisture content of the MSW, %.

The results were analyzed to detect problematic morphological components that make a predominant contribution in terms of toxic compounds and technologically important elements. For the problematic morphological components, physical properties that make it possible to separate them from target fuel components were chosen. Using the selected features, methods of MSW separation and related equipment were recommended. The content of the elements in the final fuel product was determined taking into account specific recovery rates of each method.

3. Results and discussion

The results of calculating undesirable chemical elements distribution between morphological components of MSW showed in Table 2(a) and Table 2(b).

| Morphological component | Ash content, wt % | Chemical element (additional with the morphological component, fraction of the total concentration in MSW), wt % |
|-------------------------|-------------------|--------------------------------------------------------------------------------------------------|
|                         |                   | SO$_3$  | P$_2$O$_5$ | Na$_2$O | Cl    | Cd    | Cr/Cr$_2$O$_3$ | Cu    | Hg    | Ni    | Pb    | Zn    |
| Paper and cardboard     | 7.8               | 27.8   | 3.7        | 4.6     | 3.3   | 0.3   | 0.8             | 3.6   | 1.4   | 2.2   | 0.5   | 1.0   |
| Food waste              | 3.1               | 13.8   | 32.1       | 7.0     | 16.0  | 0.2   | 0.2             | 0.3   | 0.2   | 0.4   | 0.1   | 0.4   |
| Landscaping waste       | 2.2               | 3.9    | 5.5        | 0.5     | 1.9   | 0.2   | 0.1             | 0.2   | 0.6   | 0.2   | 0.5   | 0.9   |
| Glass                   | 31.7              | 5.8    | 1.4        | 73.2    | 0     | 0.5   | 50.8            | 0.5   | 1.5   | 50.9  | 11.3  | 1.0   |
| Stone                   | 2.1               | 0.0    | 0.5        | 2.6     | 3.3   | 0.0   | 0.1             | 0.1   | 0.0   | 0.2   | 0.1   | 0.1   |
| Metal (nonferrous)      | 2.2               | 0.0    | 0.1        | 0.0     | 0.0   | 0.1   | 0.6             | 3.7   | 0.2   | 1.4   | 0.2   | 0.2   |
| Metal (ferrous)         | 11.4              | 0.4    | 1.2        | 0.6     | 0.0   | 2.1   | 4.6             | 8.5   | 1.0   | 17.1  | 1.1   | 2.5   |
| Polymers (PET bottles,  | 0.9               | 9.5    | 2.3        | 1.7     | 4     | 0.7   | 3.4             | 3.7   | 0.4   | 1.1   | 23.4  | 5.6   |
| polyethylene, and       |                   |        |            |         |       |       |                 |       |       |       |       |       |
| polypropylene)          |                   |        |            |         |       |       |                 |       |       |       |       |       |

Table 2(b). Distribution of the undesirable chemical elements between the morphological components of MSW.
MSW.

Analysis of the distribution of the chemical elements between the morphological components of MSW demonstrated practically important results. The great bulk of contaminants were concentrated in a limited list of morphological components. For example, batteries are the main carrier of mercury (89%), batteries and electronics are the main carriers of cadmium (87%). A considerable mass of lead and zinc (25 and 27%, respectively) is concentrated in siftings (a fine fraction smaller than 10 mm, which contains sand and street sweepings), and 88% chromium is distributed among green glass, textiles, footwear. The impact of these elements on cement production process and cement quality is described in [1].

The list of the fractions whose extraction is reasonable is limited by the following 12 morphological components: siftings, glass, nonferrous metals, ferrous metals, electronics, batteries, stone, ceramics, food waste, textiles, other (chlorine-containing) polymers, and footwear. The extraction of these components will make it possible to remove the bulk of heavy metals from fuel, to decrease ash content, and to stabilize fuel chemical composition. The supply of technologically important oxides will be decreased, which is in line with the proposed approach.

For the problematic morphological components, the physical attributes of distinction from target fuel fractions have been chosen. Taking into account the selected attributes, a combination of separation methods and related equipment were recommended (Table 3(a) and Table 3(b)).

Table 3(a). Recommended separation methods for production of solid fuel from MSW.

| Undesirable morphological component of MSW | Equipment recommended for separation | Principal (secondary) contrast attribute | Estimated component specific recovery in the method, % | Total component recovery, % |
|------------------------------------------|-------------------------------------|------------------------------------------|-------------------------------------------------------|-----------------------------|
| Food waste                               | Vibrating finger screen             | Elasticity (size)                         | 85                                                    | 85                          |
| Siftings                                 | Vibrating finger screen             | Size (density)                            | 70                                                    | 97                          |
|                                          | Disc screen (opening size 50 mm)     | Size (density)                            | 90                                                    |                             |
Table 3(b). Recommended separation methods for production of solid fuel from MSW.

| Undesirable morphological component of MSW | Equipment recommended for separation | Principal (secondary) contrast attribute | Estimated component specific recovery in the method, % | Total component recovery, % |
|-------------------------------------------|--------------------------------------|------------------------------------------|-----------------------------------------------------|-----------------------------|
| Stone, ceramics                           | Vibrating finger screen              | Size (density)                           | 85                                                  | 89                          |
|                                           | Disc screen (opening size 50 mm)     | Size (density)                           | 30                                                  |                             |
| Glass                                     | Disc glass-breaker screen            | Fragility, size (density)                | 80                                                  | 80                          |
| Ferrous metals                            | Electromagnetic separator            | Magnetic properties                      | 90                                                  | 99                          |
| Nonferrous metals                         | Eddy current separator               | Appearance of electromagnetic induction forces in a variable field | 90                                                  | 99                          |
| Electronics                               | Manual sorting                       | Visual distinction                       | 50                                                  | 87                          |
|                                           | Eddy current separator / X-ray separator | Appearance of electromagnetic induction forces in a variable field / Specific shape | 80/90                                               |                             |
| Batteries                                 | Manual sorting for large (car) batteries | Visual distinction                       | 50                                                  | 98                          |
|                                           | Electromagnetic separator            | Magnetic properties                      | 70                                                  |                             |
|                                           | Disc screen (opening size 50 mm)     | Size (density)                           | 75                                                  |                             |
| Textiles                                  | Manual sorting                       | Visual distinction                       | 70                                                  | 70                          |
| Other (chlorine-containing) polymers, footwear | NIR-separation / manual sorting     | Optical properties / visual distinction  | 95/50                                               | 50-95                       |

The application of the proposed methods combination to mixed MSW typical of Russia has been modelled using known performance of the methods for each morphological component. The figure shows the results of separation, which can be considered as a favourable outcome on all relevant heavy metals and chlorine. The 12 undesirable components that have been focused on in the framework of the research account for about 50% of the initial MSW on a wet weight basis. The estimated fuel yield is 34.7% of the mass of the initial waste (without taking into account food fraction that can be dried and returned to the fuel), the ash content is 13.5%. In regular practice, the yield of fuel is 20%. Taking the values into consideration, the conclusion can be made that the proposed approach allows increasing the performance of SRF production, but still there is a reserve for the yield increase through the development of more effective separation equipment.
Figure 1. Results of the application of the recommendations to the mixed MSW typical of Russia [1].

The calculation is performed under the condition that the wet biodegradable fraction (mainly food waste) is not included in the fuel composition. If it is dried and added to the fuel, the content of heavy metals will decrease, but the chlorine content will increase significantly, suggesting that composting or anaerobic digestion are more preferable options for food waste.

The results described should be interpreted with consideration for the possible deviations of values that occur in practice from the data used in this work [1]. The significance of these deviations for the results interpretation is reduced due to the intentional use of the maximally measured average concentrations of contaminants in MSW and the most rigid requirements imposed on the quality of fuel.

A certain error can be related to the presence of the “others” that is a composition of many insignificant morphological components. Researchers may include various components in this group. Therefore, data on the composition of “others” are incomparable, and the contaminants contained in “others” can not be taken into account in the calculations. It is possible only to note that about 50% of the “others” is smaller than 50 mm, and can be extracted to a considerable degree during screening.

4. Conclusion
It was showed that in order to reduce the content of undesirable substances it is necessary to specifically extract the carriers of undesirable substances, namely the following components of MSW: glass, stone, metals (ferrous and nonferrous), food waste, “other” polymers (except of PET bottles, polyethylene of all kinds, and polypropylene), batteries, electronics, footwear, textiles, ceramics, and siftings. Application of methods efficient for the particular morphological components makes it possible to increase separation selectivity and to obtain fuel that satisfies the very strict requirements. This approach allows removing heavy metals from SRF and effectively reducing ash content with a minimum loss of calorific components, stabilizing the ash composition at the same time.

5. References
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