# Valorisation of materials within Enhanced Landfill Mining: what is feasible?

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## Abstract

The main objective of Enhanced Landfill Mining is the valorisation of the excavated waste materials that have been stored in the landfill. Previous landfill mining projects have shown that different landfill sites have different potential with regard to landfill mining. In the present article, the valorisation options for the materials stored at the Remo landfill site in Houthalen are assessed based on excavation tests done at locations containing either municipal solid waste (MSW) or industrial waste (IW). The results reveal differences in the composition and the characteristics of the waste materials with regard to type of waste (MSW versus IW) and the period during which the waste was stored. For MSW the maximum amount of materials suitable for material valorisation varies between 40-60% depending on the duration during which the waste was landfilled, while for IW the maximum amount was estimated at 72%. The development of a treatment plant that enables maximum material valorisation remains one of the challenges of the Enhanced Landfill Mining project.

## Introduction

In the last decade new technologies and processes have emerged that enable more efficient recycling of materials from often complex and heterogeneous waste streams.[1,2,3] The principal drivers for these developments are the local and EU legislation on waste (Directive 2008/98/EC), as well as the growing demand for metals, high quality recycled aggregates and waste derived fuels. Both the legislative framework and increasing market prices for the recycled materials create conditions that justify the development of new waste recycling and separation technologies.[2,4,5]

One of the main drivers of Enhanced Landfill Mining (ELFM) is the valorisation of waste materials excavated from landfills. Due to the heterogeneous nature of the waste streams in landfills, separation and treatment of the different waste streams is required to enable the generation of valuable (recycled) materials. Specific treatment and separation schemes are available for the treatment of various specific (often) heterogeneous waste streams such as shredder, bottom ashes, C&D waste and contaminated soil. Most of these schemes make use of a combination of dry and/or wet mechanical separation techniques including crushing, milling, sieving, magnetic separation of ferrous and non-ferrous metals, density separation based on air flow, water based density separation techniques, jigging, *etc.* In case of ELFM, the separation and treatment processes should go a step further than what is accomplished at existing waste treatment plants. The treatment scheme should be able to recycle and recover materials from a mixture of heterogeneous waste streams of which the composition and hence the physical and chemical properties are influenced by the age of the waste and the degradation of the waste over time. Part of the waste streams are even residues from mixtures of the residual waste originating from elaborated treatment schemes that were designed in the past to recover and recycle materials from specific waste streams.

Previous pilot and pre-feasibility studies around the world as well as completed landfill mining projects have shown that different landfill sites have different potential with regard to landfill mining.[6] Factors such as the age of the landfill, type of landfill and the country or region where the landfill is located might have an impact on the type of materials stored in the landfill and their valorisation potential. To determine the recycling potential for a specific landfill, quantitative and qualitative analysis of the waste streams stored are essential.[7]

To assess the quality of the waste streams stored at the Remo landfill site in Houthalen-Helchteren (Belgium) an exploratory field test was conducted as part of the Closing the Circle project (see also paper by Tielemans and Laevers in this volume). At the Remo landfill site around 16 million tons of waste has been landfilled since the beginning of the 1970s. Both household and industrial wastes have been landfilled. An inventory is available specifying the amount, the type and the location of the different waste streams within the landfill. Since the inventory provides no detailed information with regard to the physicochemical properties of the waste necessary to assess the valorisation potential, an exploratory field test was done at the Remo landfill site. The objectives of the field test were to:

- Evaluate differences in composition of the waste with regard to the type of waste stored (household versus industrial waste);
- Asses the variation in composition for one specific waste type;
- Investigate the impact of storage time on the composition and characteristics of the waste;
- Compare the composition of the waste with data available in the records and in literature;
- Make an assessment of the valorisation potential of the materials stored in the landfill.

## Materials and methods

### Site description

The Remo landfill site has been in operation since the start of the 1970s and is located in Houthalen-Helchteren in the province of Limburg in Belgium. The total area of the landfill containing non-hazardous waste that is considered for Enhanced Landfill Mining is about 1.286.200 $m^2$. The landfill has been divided into sections based on the type of waste stored, the period during which the section was in operation and the location in the landfill. For each section information is available with regard to the type and amount of waste stored. Roughly half of the 16,5 million tons that have been landfilled at the Remo landfill site is household waste. The other half comprises industrial waste such as shredder material from the car industry, metallurgical slags, pyrite containing slags, dried sludge, *etc.* (see also Jones *et al.* and Tielemans and Laevers in this volume). Leachate collection and treatment, soil protection measurements and methane recovery are in place and comply with the Flemish and European legislation (VLAREM, landfill Directive/1999/31/EC).

### Excavation and sampling procedure

To obtain the maximum amount of information during the field excavation tests, 6 locations were selected for further investigation. An overview of the type of waste and the time of disposal at a specific location is given in Table 1. For municipal solid waste (MSW), the maximum storage time of the waste varied between 14 and 29 years and the locations were chosen to collect data that are representative for the majority of the municipal solid waste stored at the Remo landfill site. For industrial waste only 2 locations were investigated of which the maximum storage time of the waste varied between 14 and 24 years. Since a variety of industrial waste materials have been landfilled on the site, it was decided to focus on the locations rich in old and new shredder like waste. Locations rich in metallurgical slags, pyrite containing slags, MSW-bottom ashes, sludges, *etc.* were therefore not investigated in this study.

A cactus grab crane was used to collect the waste samples up to the maximum depth of the landfill. A shaft of about 1x1 m and up to 15 m deep was excavated at each location during which waste samples were collected at each depth interval (0-1 m, 1-2 m, *etc.*) in the bucket of a wheel loader. This sample was subsequently loaded into a container in which the sample was mixed and spread out in a thin layer at the bottom of the container. Oversized (> 200 mm) objects such as boulders, metal bars and very large sheets of plastic were separated from the bulk sample and their volume/mass percentage was estimated and recorded. To collect a representative sample from each container, a grid was placed on top of the waste layer. The composition of the waste samples from two grid cells (see Figure 1) was described by visual inspection without detailed sorting. The waste samples were then stored in closed plastic buckets (30 l). During the field excavation tests around 130 samples were collected of which 38 samples were selected for further investigation.

**Table 1:** Description of sampling locations selected for the field test.

| Number | Year of storage | Type of waste | Description of waste | Depth of landfill (m) |
|---|---|---|---|---|
| 1 | 1980-1985 | MSW | Municipal solid waste originating from both households, businesses and industrial companies | 11 |
| 2 | 1985-1990 | MSW | Municipal solid waste originating from businesses and industrial companies | 13 |
| 3 | 1990-1995 | MSW | Municipal solid waste originating from businesses and industrial companies | 11 |
| 4 | 1995-2000 | IW | Industrial waste rich in shredder and fine residues such as sludge | 9 |
| 5 | 1985-1990 | IW | Industrial waste | 8 |
| 6 | 1995-2000 | MSW | Municipal solid waste originating from businesses and industrial companies | 13 |

**Figure 1:** Overview of sampling method used at the Remo landfill site to collect waste samples from a closed landfill.

### Composition and characterisation of the waste

The water content of the waste samples was assessed by drying the samples at 70°C. Each of the dried samples was then screened with a sieve mesh of 10 mm. Subsequently, the composition of the oversized fraction was determined by manual sorting into 8 sub-fractions (plastics, textile, wood, paper/cardboard, metal, glass/ceramics, stone and an undefined fraction). The weight of the different sub-fractions was determined and the physical and the chemical composition of a number representative samples was analysed after size reduction. An overview of the sample treatment scheme is presented in Figure 2. In addition to the analysis of the individual separated fractions, the chemical and physical properties of some of the non-sorted waste samples were also determined.

The dry weight of the samples was analysed according to CEN/TS 15414:2006. The ash content was determined at 550°C and 815°C according to CEN/TS 15403: 2006. The gross and net calorific values were analysed at constant pressure according to CEN/TS 15400:2006. Carbon (C), hydrogen (H) and nitrogen (N) were determined using CEN/TS 15407:2006 while sulphur (S), chlorine (Cl), fluorine (F) and bromine (Br) were analysed using CEN/TS 15408:2006. TOC and EOX were determined using CMA/2/II/A.7 and CMA/3/N, respectively, while the inorganic composition of the samples (Al, Ca, P, Fe, Mg, Mn, Na, Si, Ti, As, Cd, Cr, Ni, Cu, Hg, Pb, Zn, Te, Sn, Ba, Mn, Mo, Se, Sr and V) was analysed using CMA/2/II/A.3 and CMA/2/I/B.1.

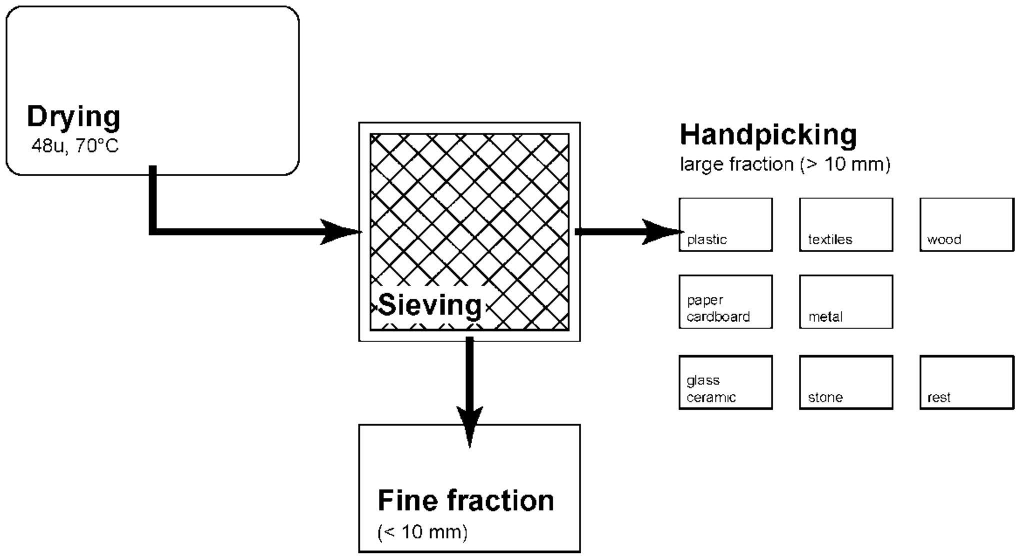


**Figure 2:** Sample pretreatment to determine composition and physical and chemical characteristics.

## Results and discussion

### Composition of the waste material

In Figure 4 an overview is given of the composition of the waste excavated at each location. Since no trend could be observed in the composition of the waste with increasing depth of the landfill, average values are presented (Figure 3). Significant differences in composition could be observed between the MSW and the IW. Although the main fraction in both the MSW and the IW was a fine soil type waste fraction, the amount present in the IW (64 ± 16%) was significantly higher than that in the MSW (44 ± 12%).

The composition of the fine fraction could not be described in detail without further investigation. It is however clear that for the MSW part of the fine fraction is composed of degraded garden and food materials. The amount of plastic, paper/cardboard and textile was higher in the MSW compared to the IW. The average moisture content of the waste samples excavated at one location varied between 48 and 66% and is comparable to previous reported values.[6,7] Although no trend in moisture content with depth could be observed during the excavation, the samples with a high moisture content were often located above a poor draining to impervious layer of material present in the landfill.

For MSW, information on the composition of waste stored during a period of 14, 19, 24, 29 year is available. Although the standard deviation of the average content of the individual fractions is large, trends can be observed for some fractions with regard to changes over time. These changes can be attributed to degradation of the waste or to changes in the composition of waste resulting from differences in waste management procedures, legislation or changes in the type of goods produced and consumed during a specific period. Due to the large standard deviation, confirmation of the trend is needed by comparison with independent data. In the Flemish region of Belgium, data on the composition of fresh municipal solid waste have been gathered since 1993.[8] In this OVAM study, the average composition of municipal solid waste collected in 2000 and 2001 was based on the analyses of about 2000 samples (total weight equal to 13 ton). At the Remo landfill site, the amount of plastic increased from 10 to 25% between 1980 and 2000. This increase probably reflects an increase in production and consumption of plastic during this period. Analysis of the composition of fresh household waste sampled between 1993 and 2000 also showed an increase in the amount of plastic (from 8 to 15%).[8] The decrease in metal content (4,3 to 2,2%) and the content of glass/ceramic (1,7 to 0,5%) over time in MSW is most likely also caused by changes in the composition of the fresh waste as confirmed by the Flemish records.[8] For the paper/cardboard content, the decrease from 16 to 11% can most

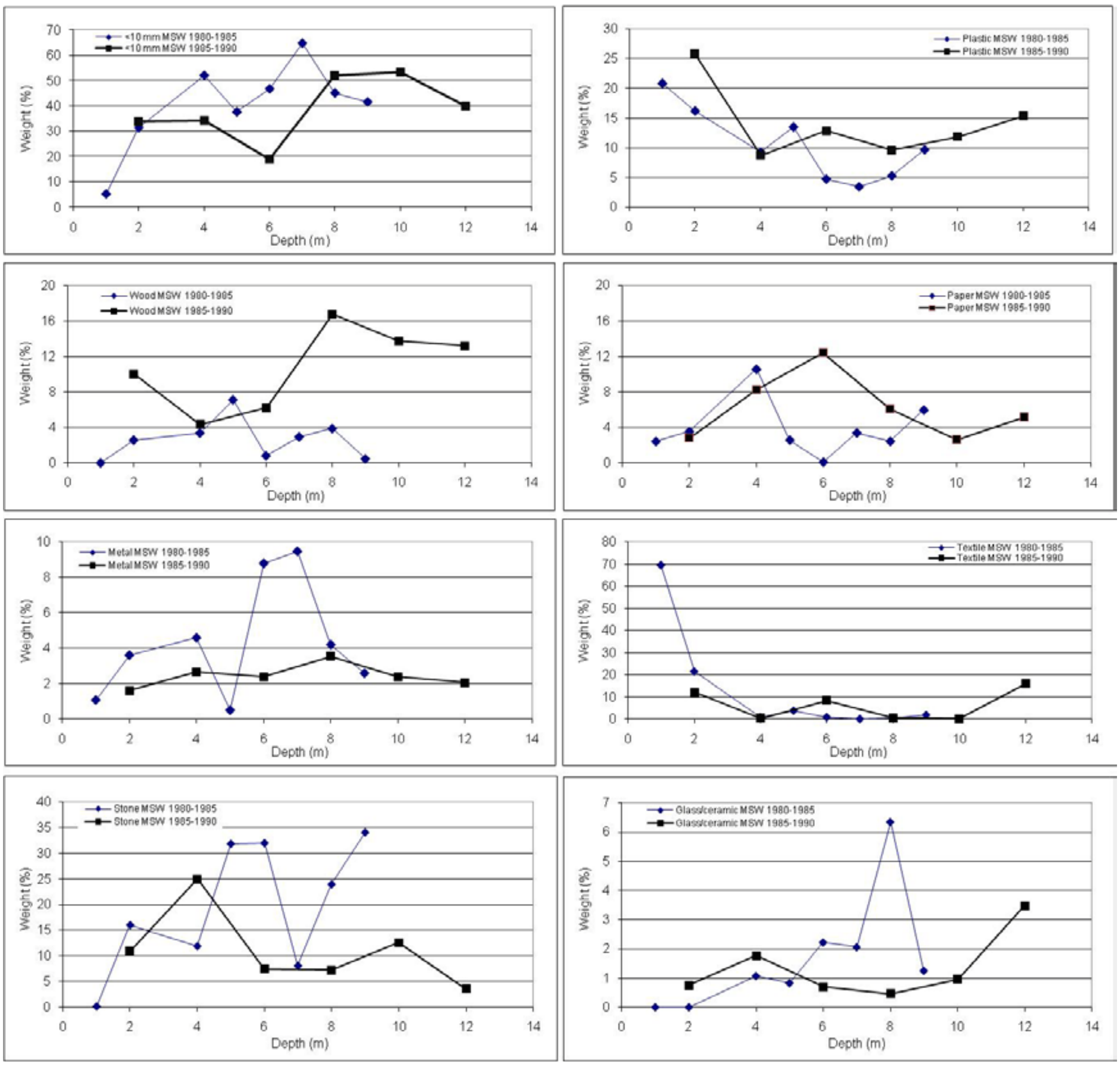


**Figure 3:** Variation in composition of municipal solid waste with depth. Results of the excavations at the Remo landfill site during the ELFM field tests. Only the results for location 1 (1980-1985) and 2 (1985-1990) are presented.

likely be attributed to degradation of the material in the landfill. Based on the Flemish records, the content of paper/cardboard in fresh household waste even seems to decrease in more recent years. Since only two locations were investigated for IW, no detailed analysis could be carried out with regard to changes in the composition for IW over time.

In Table 2 the average composition of excavated waste that was landfilled between 1995 and 2000 (collected at location 6 in the Remo landfill site field test) is compared to the composition of fresh municipal waste collected in the Flemish region of Belgium between 2000-2001.[8] The amount of glass, metal, inert, textile, paper/cardboard and plastic compares well between the fresh and aged waste. An organic fraction can however no longer be distinguished in the aged waste samples and has most likely been partially degraded during 10 years of storage. Based on a comparison with the composition of fresh waste (Table 2) it seems likely that the organic fraction of the samples has been degraded and classified in the fine fraction (or soil type waste) of the aged sample.

**Table 2:** Average composition of waste landfilled between 1995-2000 (excavated at location 6 in the Remo landfill site field test) compared to fresh MSW sampled in Flanders in 2000[8].

| | Stored waste (1995-2000) | Fresh waste (2000-2001) |
|---|---|---|

| | | |
|---|---|---|
| Glass | 0,5 | 2,4 |
| Inert fraction (Stone) | 2,0 | 3,3 |
| Metal | 2,2 | 3,2 |
| Textile | 3,1 | 2,9 |
| Other materials | 4,1 | 6,6 |
| Wood | 4,1 | - |
| Paper/cardboard | 14 | 14 |
| Plastic | 25 | 24 |
| Fine fraction (<10 mm) | 45 | - |
| Organic fraction | - | 43 |

**Characterisation of fraction < 10 mm**

The fraction < 10 mm is the major fraction in both MSW and IW and is composed of all the waste materials that pass through a sieve with a mesh size of 10 mm. Due to the unknown and heterogeneous nature of the material, this fine, soil type fraction was analysed in detail. The results of the properties relevant for thermal and material valorisation are presented in Table 3 and Table 4.

The ash content for MSW seems generally lower than the ash content for IW and is comparable to the ash content reported for the fine fraction separated from waste by Hogland *et al.*[6] The calorific value and the TOC concentration for MSW, however, seem higher than those for IW. In addition the calorific value (2,2 to 4,8 MJ/kg dw) and the TOC concentration (7,6 to 12%) in the fine fraction of MSW decrease with increasing storage time. This decrease is most likely the result of decomposition of C-rich material into landfill gas. Landfill gas is the mixture of carbon dioxide and methane, and other trace components, generated by bacterial decomposition of organic waste. Most important factors that affect methane generation include waste composition, moisture content, temperature, waste nutrient level, and the presence or absence of buffering agents (which may be provided from such sources as cover soils)[9]. In this study, the average degradation can be described reasonably well with a


**Figure 4:** Variation in composition and moisture content for municipal solid waste and industrial waste that had been stored in the Remo landfill site between 9 and 29 years.

first order decay curve [$C(t) = C_0\, e^{-kt}$; $R^2$ = 0.92, $C_0$ = 21%; $k$ = 0,0343 year$^{-1}$] (Figure 5). The factor 'C0' represents the concentration of TOC in the fine fraction of MSW at the time of burial. *k* is the first order rate constant and reflects the rate at which the degradation of carbon-rich material occurs. The estimated value can be compared to the first order rate constant often used in models to predict methane recovery from landfills. Although various type of models are available, simple first order models have been used successfully to describe and predict landfill gas generation[9,10] with *k*-values ranging between 0,02 year$^{-1}$ en 0,10 year$^{-1}$.

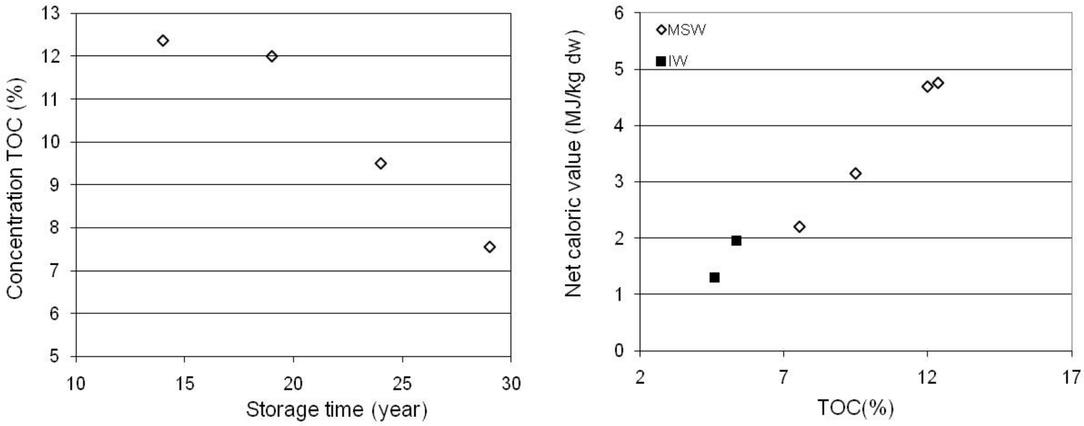


**Figure 5:** Relation between average concentration of TOC and maximum storage time of the 'soil type' waste fraction separated from MSW at the Remo landfill site (left). Correlation between calorific value and average TOC concentration for the 'soil type' waste fractions separated from excavated MSW and IW landfilled between 1980-2000 at the Remo landfill site

The concentrations of major and minor elements determined in the fine, soil type fraction are presented in Table 4. The average chemical composition of the fine fraction separated from IW clearly contains more Ca, Fe and metals such as Cr, Cu, Ni, Pb and Zn compared to the soil type fraction originating from MSW. For MSW, a decrease in the concentration of As, Cd, Cr, Cu, Hg, Ni, Pb and Zn with decreasing storage time could be observed and can most likely be attributed to an improved quality of the MSW landfilled over time. A magnet was subsequently used to determine the amount of ferro metals in the soil type fraction (Table 4). The magnetic fraction in the fine fraction from IW was significantly higher (25 - 29%) than the magnetic fraction from MSW (0,5 - 5,3%).

For MSW, an increase in the amount of magnetic material was observed with increasing age of the waste, which could reflect the improved quality of the municipal solid waste over time. Since the magnetic fraction separated from the soil type fraction was still a mixture of metals, oxides and other minerals, XRF analysis after ashing combined with microscopic analyses was used to determine the amount and speciation of the metals present in the magnetic fraction (Table 4). The amount of metallic iron in the magnetic fraction was estimated between 8 and 9% with the metallic iron often embedded in an oxide rich matrix Figure 6.

**Table 3:** Average characteristics of the soil type waste fraction (<10 mm) separated from waste samples excavated at the Remo landfill site during the field test with standard deviation (STDEV).

| Location | 1 | | 2 | | 3 | | 6 | | 5 | | 4 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Type | MSW | | MSW | | MSW | | MSW | | IW | | IW | |
| Age | 1980-1985 | | 1985-1990 | | 1990-1995 | | 1995-2000 | | 1985-1990 | | 1995-2000 | |
| | Average (%) | STDEV | Average (%) | STDEV | Average (%) | STDEV | Average (%) | STDEV | Average (%) | STDEV | Average (%) | STDEV |
| Ashcontent (815°C) | 85 | 7 | 77 | 2 | 64,4 | - | 80,9 | 5 | 87,5 | - | 85,2 | 2 |
| Total carbon (%) | 7,8 | 5 | 11 | 0,8 | 14,7 | - | 11,3 | 5 | 5,93 | - | 7,1 | 5 |
| TOC (%) | 7,6 | 3 | 9,5 | 0,4 | 12 | - | 12,4 | 5 | 4,6 | - | 5,4 | 3 |
| Hydrogen (H) (%) | 0,88 | 0 | 1,2 | 0,1 | 1,7 | - | 1,1 | 0,1 | 0,81 | - | 1,2 | 0,2 |
| Nitrogen (N) (%) | 0,39 | 0,2 | 0,53 | 0,0 | 0,66 | - | 0,39 | 0,1 | 0,3 | - | 0,28 | 0,1 |
| Net caloric value (MJ/kg ds) | 2,2 | 0,7 | 3,2 | 0,5 | 4,7 | - | 4,8 | 2 | 1,3 | - | 2,0 | 2 |
| Bruto caloric value (MJ/kg ds) | 2,4 | 0,8 | 3,4 | 0,6 | 5,7 | - | 5,0 | 2 | 2,3 | - | 2,1 | 2 |
| Bromide (%) | 0,03 | 0 | 0,03 | 0,0 | 0,03 | - | 0,03 | 0,0 | 0,025 | - | 0,03 | 0 |
| Chloride (%) | 0,15 | 0,02 | 0,41 | 0,2 | 0,26 | - | 0,26 | 0,2 | 0,17 | - | 0,36 | 0,09 |
| Fluoride (%) | 0,009 | 0,005 | 0,01 | 0,0 | 0,009 | - | 0,02 | 0,0 | 0,3 | - | 0,38 | 0,5 |
| Suphur (%) | 0,19 | 0,1 | 0,26 | 0,1 | 0,23 | - | 0,22 | 0,1 | 0,31 | - | 1,5 | 2 |

**Table 4:** Average concentrations with standard deviation (STDEV) of major and minor elements of the soil type waste fraction (<10 mm) separated from MSW and IW waste samples excavated at the Remo landfill site during the field test.

| Nr | Type | Year | Si | Ca | Fe | metallic | EOX als Cl | As | Cd | Cr | Cu | Hg | Ni | Pb | Zn |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | g/kg | g/kg | g/kg | (%) | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg |
| 1 | MSW | 1980-1985 | 260 (57) | 31 (17) | 34 (23) | 5,3 (0,9) | 715 (686) | 61 (30) | 8,5 (8) | 770 (325) | 285 (78) | 2,0 (2) | 335 (134) | 500 (396) | 670 (297) |
| 2 | MSW | 1985-1990 | 235 (35) | 35 (1) | 39 (4) | 5,0 (4) | 960 (481) | 31 (28) | 8,4 (5) | 380 (141) | 205 (106) | 0,50 (0,1) | 164 (107) | 310 (184) | 735 (219) |
| 3 | MSW | 1990-1995 | 220 (-) | 33 (-) | 18 (-) | 1,4 (-) | 670 (-) | 7,2 (-) | 3,3 (-) | 720 (-) | 760 (-) | 0,27 (-) | 160 (-) | 180 (-) | 800 (-) |
| 6 | MSW | 1995-2000 | 243 (6) | 14 (7) | 17 (3) | 0,5 (0,08) | 1787 (2872) | 9,1 (2) | 3,3 (2) | 113 (6) | 107 (37) | 0,19 (0,1) | 46 (2) | 172 (89) | 463 (329) |
| 5 | IW | 1985-1990 | 230 (-) | 73 (-) | 53 (-) | 30 (5) | 410 (-) | 19 (-) | 15 (-) | 3800 (-) | 1200 (-) | 2,4 (-) | 2200 (-) | 1100 (-) | 2600 (-) |
| 4 | IW | 1995-2000 | 181 (126) | 78 (88) | 54 (8) | 25 (-) | 284 (334) | 22 (6) | 19 (1) | 5730 (7453) | 5750 (6010) | 0,99 (1) | 4640 (6166) | 2640 (2489) | 5600 (849) |
| VLAREBO limit values unrestricted use of soil (mg/kg)* | | | | | | | | **18,9** | **1,8** | **91** | **123** | **1,7** | **56** | **120** | **457** |
| VLAREBO limit values for contaminated soil (type III) (mg/kg)* | | | | | | | | **103** | **6** | **240** | **353** | **4,8** | **95** | **560** | **761** |
| VLAREBO limit values for use of soil in or as construction material (mg/kg) | | | | | | | | **250** | **10** | **880** | **375** | **5** | **250** | **1250** | **1250** |
| VLAREA limit values for use of waste as soil fertilizer and compost (mg/kg) | | | | | | | | **103** | **6** | **240** | **197** | **4,8** | **95** | **560** | **333** |
| VLAREA guidance value for use of waste in or as construction materials(mg/kg) | | | | | | | | **250** | **10** | **1250** | **375** | **5** | **250** | **1250** | **1250** |

*Calculated with 2% clay and 10% OM

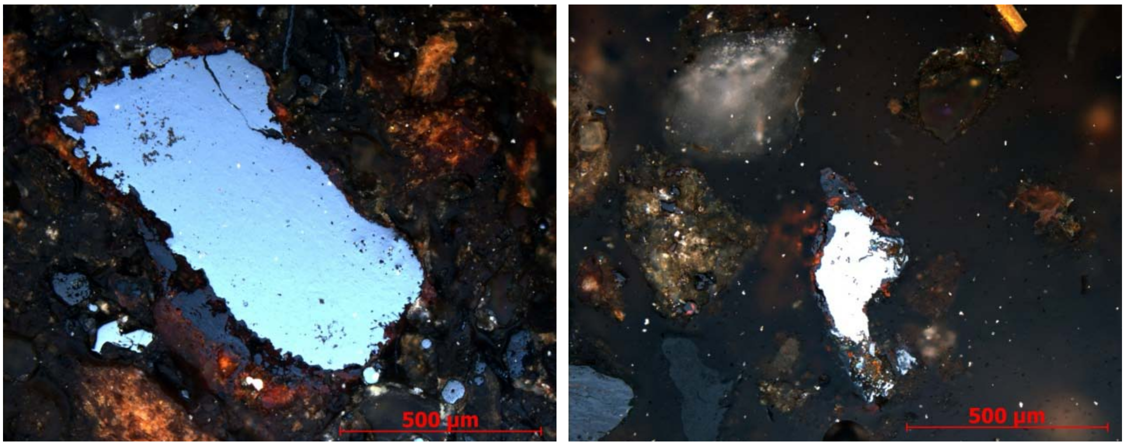


**Figure 6:** Photomicrographs of thin-sections made from the magnetic fraction of the soil type waste fractions showing details of a metallic Fe particle embedded by iron-oxide from IW landfilled in 1995-2000 (left) and IW landfilled in 1985-1990 (right)

### Characteristics of plastics

The plastic fraction is characterised by an elevated ash content (20-35%) and a lower calorific value (19-28 MJ/kg) compared to the ash content and calorific value of mixed plastic streams reported in literature (Phyllis database) (ash content: 1%; calorific value: 35 MJ/kg daf) (Table 5 and Table 6). Since the plastics were separated from the waste by handpicking without further washing or treatment it is likely that some dust or sand particles sticking to the plastics influenced the measurements. The chloride concentration varied between 0,5 - 7,3%.

In this study, no differences could be observed in TOC concentration and calorific value between the plastic fraction separated from IW versus MSW. The amount of TOC compares well with values reported for plastics in MSW in the Netherlands (59%).[11] The plastic fraction separated from IW, seems to contain higher concentration of metals such as Ba, Cd, Cr, Cu, Pb and Zn compared to the plastic fraction from MSW. No indication was found that the thermal properties change with increasing storage time of the waste.

**Table 5:** Average characteristics with standard deviation (STDEV) of the plastics separated from waste samples excavated at the Remo landfill site during the field test.

| **Location** | 1 | | 2 | | 3 | | 6 | | 5 | | 4 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Type** | **MSW** | | **MSW** | | **MSW** | | **MSW** | | **IW** | | **IW** | |
| **Age** | **1980-1985** | | **1985-1990** | | **1990-1995** | | **1995-2000** | | **1985-1990** | | **1995-2000** | |
| | Average (%) | STDEV | Average (%) | STDEV | Average (%) | STDEV | Average (%) | STDEV | Average (%) | STDEV | Average (%) | STDEV |
| Ashcontent (815°C) | 25 | 2 | 32 | - | 38 | - | 20 | - | 23 | - | 35 | 2 |
| Total carbon (%) | 50 | 2 | 44 | - | 41 | - | 59 | - | 57 | - | 39 | 7 |
| TOC (%) | 57 | 4 | 51 | - | 53 | - | 67 | - | 58 | - | 37 | 16 |
| Hydrogen (H) (%) | 6,7 | 1 | 7 | - | 6,0 | - | 8,1 | - | 6,9 | - | 5,4 | 0,2 |
| Nitrogen (N) (%) | 0,7 | 0 | 1 | - | 0,59 | - | 0,2 | - | 0,7 | - | 0,75 | 0,5 |
| Net caloric value (MJ/kg ds) | 24 | 3 | 21 | - | 18 | - | 27 | - | 26 | - | 21 | 4 |
| Bruto caloric value (MJ/kg ds) | 25 | 3 | 23 | - | 19 | - | 28 | - | 28 | - | 22,1 | 4 |
| Bromide (%) | < 0,025 | - | < 0,025 | - | < 0,025 | - | < 0,025 | - | < 0,025 | - | < 0,025 | - |
| Chloride (%) | 7,3 | 3 | 0 | - | 1,8 | - | 5,5 | - | 3,9 | - | 1,6 | 1 |
| Fluoride (%) | 0,01 | 0 | 0 | - | 0,006 | - | 0,0 | - | 0,056 | - | 0,061 | 0,03 |
| Suphur (%) | 0,2 | 0 | 0 | - | 0,27 | - | 0,2 | - | 0,47 | - | 0,42 | 0,01 |

**Table 6:** Average concentrations of major and minor elements of the plastic fraction separated from MSW and IW waste samples excavated at the Remo landfill site during the field test.

| Nr | Type | Year | Si | Ca | Fe | EOX Cl | As | Ba | Cd | Cr | Cu | Hg | Ni | Pb | Zn |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | g/kg | g/kg | g/kg | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg |
| 1 | MSW | 1980-1985 | 68 | 13 | 18 | 53333 | 33 | 430 | 51 | 490 | 1767 | 0,6 | 327 | 550 | 1063 |
| 2 | MSW | 1985-1990 | 110 | 20 | 26 | 380 | 6,9 | 540 | 18 | 320 | 150 | 0,36 | 86 | 280 | 620 |
| 3 | MSW | 1990-1995 | 100 | 15 | 13 | 9600 | 6,2 | 600 | 19 | 280 | 690 | 0,46 | 73 | 230 | 1700 |
| 6 | MSW | 1995-2000 | 41 | 7,8 | 10 | 39000 | 7,6 | 110 | 18 | 270 | 270 | 0,1 | 740 | 160 | 470 |
| 5 | IW | 1985-1990 | 72 | 26 | 23 | 3800 | 9,9 | 2300 | 47 | 780 | 10000 | 2,0 | 640 | 1300 | 5500 |
| 4 | IW | 1995-2000 | 74 | 17,5 | 38 | 1860 | 12 | 3600 | 41 | 530 | 2405 | 1,1 | 275 | 1900 | 3800 |

## Characterisation of paper/cardboard

Only the paper/cardboard fractions separated from MSW have been analysed. The paper/cardboard fraction is characterised by a high and variable ash content (25-61%) (Table 7). The TOC concentration varies between 25 and 34% and is comparable to the TOC concentration reported for paper in MSW (27%).[11] The net calorific value varied between 6,7 and 12 MJ/kg dw and is slightly lower than the calorific value reported for mixed paper streams (15 MJ/kg dw). The metal concentration is generally lower than the concentration reported for the plastic fraction (Table 8).

**Table 7:** Average characteristics with standard deviation (STDEV) of the paper/cardboard separated from waste samples excavated at the Remo landfill site during the field test

| **Location** | 1 | | 2 | | 3 | | 6 | |
|---|---|---|---|---|---|---|---|---|
| **Type** | **MSW** | | **MSW** | | **MSW** | | **MSW** | |
| **Age** | **1980-1985** | | **1985-1990** | | **1990-1995** | | **1995-2000** | |
| | Average (%) | STDEV | Average (%) | STDEV | Average (%) | STDEV | Average (%) | STDEV |
| Ashcontent (815°C) | 43 | - | 61 | - | 25 | - | 35 | - |
| Total carbon (%) | 32 | - | 23 | - | 34 | - | 33 | - |
| TOC (%) | 34 | - | 25 | - | 33 | - | 31 | - |
| Hydrogen (H) (%) | 3,9 | - | 2,6 | - | 4,0 | - | 3,7 | - |
| Nitrogen (N) (%) | 0,7 | - | 0,7 | - | 0,8 | - | 0,7 | - |
| Net caloric value (MJ/kg ds) | 11 | - | 6,7 | - | 12 | - | 12 | - |
| Bruto caloric value (MJ/kg ds) | 12 | - | 7,3 | - | 13 | - | 13 | - |
| Bromide (%) | < 0,025 | - | < 0,025 | - | < 0,025 | - | < 0,025 | - |
| Chloride (%) | 0,50 | - | 0,43 | - | 0,17 | - | 0,28 | - |
| Fluoride (%) | 0,01 | - | 0,01 | - | 0,01 | - | 0,01 | - |
| Suphur (%) | 0,31 | - | 0,19 | - | 0,31 | - | 0,90 | - |

**Table 8:** Average concentrations of major and minor elements of the plastic fraction separated from MSW waste samples excavated at the Remo landfill site during the field test

| Nr | Type | Year | Si | Ca | Fe | EOX als Cl | As | Ba | Cd | Cr | Cu | Hg | Ni | Pb | Zn |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | g/kg | g/kg | g/kg | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg | mg/kg |
| 1 | MSW | 1980-1985 | 100 | 17 | 26 | 1300 | 39 | 240 | 1,4 | 310 | 150 | 0,45 | 120 | 440 | 900 |
| 2 | MSW | 1985-1990 | 130 | 32 | 29 | 640 | 9,7 | 480 | 16 | 200 | 210 | 0,27 | 56 | 330 | 560 |
| 3 | MSW | 1990-1995 | 88 | 27 | 6,5 | 270 | 4,9 | 180 | <0.40 | 140 | 570 | 0,38 | 45 | 54 | 520 |
| 6 | MSW | 1995-2000 | 91 | 33 | 30 | 260 | 5,5 | 280 | 2,7 | 160 | 100 | 0,35 | 86 | 380 | 1900 |

### Valorisation options

Based on the composition of the waste and the characteristics of the individual fractions separated from the waste, the valorisation options were assessed. It should however be noted that handpicking was used to separate individual fractions from the original waste samples in this study. During full scale excavation of the landfill, a specific treatment plant will be designed to treat and separate the waste which could result in different characteristics (ash content, chemical composition, *etc.*) or purity compared to the fractions obtained during this study by handpicking. Although a variety of industrial waste materials have been stored at the Remo landfill site, only locations rich in shredder type waste were investigated in the field test. For IW only the valorisation options for shredder type waste material will therefore be evaluated.

***Fine soil type fraction.*** For both IW and MSW more than 40% of the waste material was classified as a 'fine soil type fraction'. Since this fraction is a combination of all the materials that pass through a 10 mm sieve further treatment and fractionation will be required to optimise the valorisation of the materials contained in this fraction. Since this fraction still contains a large amount of organic material, separation might result in a fraction suitable for 'energy valorisation'. Based on the chemical composition a large portion of the remaining fraction might be suitable for valorisation as construction material. It is however clear that the quality of the fine fraction resulting from MSW is better than the quality of the material separated from IW due to the elevated metal concentrations (Cd, Cr, Cu, Ni, Pb and Zn) in the fine fraction composed of IW. One of the options to reduce the concentration of metals such as Cr, Cu, Ni, Zn, is to separate and remove the magnetic fraction from the fine fraction. Although only preliminary results are available, removal of the magnetic fraction could result in a reduction in concentration of metals of more than 50%. This can be explained by the high amount of metal-oxides associated with metallic iron (see Figure 6). For MSW, a decrease in the concentration of As, Cd, Cr, Cu, Hg, Ni, Pb and Zn can be observed with decreasing storage time of the waste. The concentrations of metals in the fine fraction of the most recently landfilled waste (1995-2000) approach the limit value for unrestricted reuse of excavated soil (Table 4).

Further research including leaching tests and determination of the concentrations of organic contaminants will be conducted on subfractions of the treated soil type fraction to further asses the valorisation options. An overview of the initial valorisation options for the soil type fraction is given in Figure 7.

***Metals, glass/ceramic and stone.*** Although the characteristics of these fractions are not presented in this paper, large part of these materials might be suitable for material valorisation. Further research including leaching tests and determination of organic contaminants will be required to further assess the valorisation options. For MSW, the metal fraction consists mainly of ferro metals (75-84%) while the remaining non-ferro is mainly aluminium (> 90%).[8] For IW, more variation can be expected.


**Figure 7 :** Overview of the valorisation options for the fine fraction (<10 mm) separated for MSW (left) and IW (right) at the Remo landfill site during the field test.

***Paper/cardboard, textile, wood and plastic.*** For a considerable fraction of the plastic, textile, paper/cardboard and wood excavated from the landfill, 'energy recovery' with valorisation of the slag residues seems the most feasible valorisation option. The quality and state of the textiles recovered from the landfill, makes direct reuse as textile not an option. Likewise, the heterogeneity of the paper/cardboard, wood and plastic fractions hampers their direct valorisation as material.

***Material versus energy valorisation.*** Based on the characteristics of the individual fraction and the composition of the waste material, the maximum amount of material suitable for material valorisation was estimated between 40-60% for MSW depending on the duration of storage in the landfill (the longer the storage period, the higher the amount). For IW the maximum percentage of waste suitable for material valorisation was estimated at 63%.

## Conclusions

In this paper an overview is given of the composition and the characteristics of the waste materials stored at the Remo landfill site based on data obtained during a field excavation study. The results reveal differences in the composition and the characteristics of the waste materials with regard to type of waste (MSW versus IW) and the period during which the waste was stored. For MSW the maximum amount of materials suitable for material valorisation varies between 40-60% depending on the duration during which the waste was stored at the landfill, while for IW (locations rich in shredder type waste) the maximum amount was estimated at 72%. The development of a treatment plant that enables maximum material valorisation remains one of the challenges of the Enhanced Landfill Mining project.

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