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CASE STUDY ON ENHANCED LANDFILL MINING AT MONT-SAINT-GUIBERT LANDFILL IN BELGIUM: PHYSICO-CHEMICAL CHARACTERIZATION AND VALORIZATION POTENTIAL OF COMBUSTIBLES AND INERT FRACTIONS RECOVERED FROM FINE FRACTIONS

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ABSTRACT

The fine fractions account for the largest share of material recovered through (enhanced) landfill mining. These fractions typically present challenging characteristics for processing and valorization methods and, hence, they have been largely discarded in previous landfill mining projects. This situation has hindered the economic and environmental feasibility of landfill mining, since most of the excavated waste has been directed back into the landfill. Therefore, the fine fractions are one of the major challenges faced by (enhanced) landfill mining and suitable material and energy recovery schemes for these fractions need to be further developed and, if necessary, created. To this end, the physico-chemical characteristics of the "Combustibles" and "Inert" fractions recovered from the fine fractions <90 mm through a dry-mechanical process have been determined and their suitability for waste-to-material and waste-to-energy schemes has been evaluated in the MSG case study. The recovered "Combustibles" fractions represented 12.5 wt.% and 9.0 wt.% of the fine fractions <90 mm processed in the optimal water content and dry states, while the recovered "Inert" fractions accounted for 35.5 wt.% and 37.2 wt.%, respectively. According to the EN 15359:2011, the "Combustibles" fractions could be valorized as SRF in (co-)incineration, power and cement plants in both the optimal water content state and the dry state in the EU. However, in Austria these fractions can only be incinerated and not co-incinerated according to the Austrian Waste Incineration Ordinance (AVV), since in some cases they present concentrations of As, Cd, Co, Hg and Pb above the limit values. Therefore, in contrast to conventional (co-)incineration, the plasma gasification process proposed by the NEW-MINE project might offer a potential waste-to-energy valorization route for the combustible fractions obtained from the fine fractions of landfill-mined waste. As for the "Inert" fractions, there is no overarching legislation in the EU to regulate such materials yet in place and, hence, these fractions are solely subject to national or local regulations on recycling building materials. In Austria the "Inert" fractions would need further treatment in order to be valorized as a substitute for construction aggregates according to the Austrian Recycling Building Materials Ordinance (RBV), as they exceed the limit values for hydrocarbons, Cd, Pb, Zn, NH₄⁺ and anionic surfactants in certain cases. Therefore, suitable waste-to-material valorization schemes for the recovered inert fractions from the fine fractions of landfill-mined waste are to be further developed, while appropriate overarching regulations need to be created at EU level.

1. INTRODUCTION

In many cases landfill mining (LFM) has failed as a business model and it has mainly been carried out within the framework of contaminated sites remediation to address the threat that landfills and dumpsites pose to the

health and well-being of the environment. However, the development of novel technologies is aiming to eventually bridge the gap between the practically possible and the economically feasible, and might gradually enable further material and energy recovery from landfill-mined material,



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as well as facilitate its integration into current waste management systems (Hernández Parrodi et al., 2019b). For this purpose, suitable valorization routes for the outputs of LFM need to be further developed and, if necessary, created. For example, in the case of the recovered combustible fractions some projects have investigated their traditional co-incineration in cement plants (Wolfsberger et al., 2015), whereas others have aimed for non-conventional routes of energy recovery through alternative thermo-chemical processes, such as pyrolysis and gasification, which might allow the upcycling of their residues into higher value glass-ceramics (Monich, Romero, Höllen, & Bernardo, 2018; Rabelo Monich, Vollprecht, & Bernardo, 2020) and inorganic polymer binders (Ascensão, Marchi, Segata, Faleschini, & Pontikes, 2019; Machiels et al., 2017). The latter approach is addressed in the enhanced landfill mining (ELFM) concept, which has been put to test in a case study at the Mont-Saint-Guibert (MSG) landfill site in Belgium. The MSG landfill case study is being carried out within the framework of the EU Training Network for Resource Recovery through Enhanced Landfill Mining - NEW-MINE. As defined by Jones et al., 2013, ELFM is the safe conditioning, excavation and integrated valorization of historic and/or future landfilled waste streams as both materials (Waste-to-Material (WtM)) and energy (Waste-to-Energy (WtE)), using innovative transformation technologies and respecting the most stringent social and ecological criteria.

One of the main challenges in (E)LFM are the fine fractions, since they present difficult characteristics for their processing and valorization, and can account for 40-80 wt.% of the total amount of landfill-mined waste (Hernández Parrodi, Höllen, & Pomberger, 2018a). The fine fractions have been frequently defined as the material with a particle size <60 mm to <10 mm in previous (E)LFM studies (Hernández Parrodi et al., 2018a); however, there is no convention in that regard to date. Furthermore, one commonly chosen alternative in prior projects has been to classify the fine fractions as a residual fraction and direct them back into the landfill (Bhatnagar et al., 2017; Kaartinen, Sormunen, & Rintala, 2013; Münnich, Fricke, Wanka, & Zeiner, 2013), which has had a critical impact on the economic and environmental feasibility of LFM projects. Therefore, the recovery of material and energy from the fine fractions has been included into the scope of the MSG case study. To this end a mechanical processing approach was designed and applied to the fine fractions in the optimal water content (owc) and dry states, according to the results of the material characterization of the fine fractions reported by Hernández Parrodi et al., 2019a and the strategies for WtM and WtE proposed in Hernández Parrodi, Höllen, & Pomberger, 2018b. In the MSG case study the fine fractions are the material with a particle size <90 mm and the owc state corresponds to a water content of around 15 wt.%. The owc state aims at minimizing material losses in the form of dust and small particle-sized and light materials, as well as decreasing the amount of energy required in the drying process. In addition, the owc should not compromise the effectivity and efficiency of a dry-mechanical processing approach. Hence, the mechanical processing approach of the MSG case study was tested in both the owc and dry

states, in order to study and evaluate the effects of the owc in terms of the processability of the fine fractions <90 mm and the quality of the produced material fractions. The tested approach consisted of a series of mechanical processing steps, which classified the fine fractions <90 mm into different material fractions and particle size ranges according to their physical properties, such as particle size, shape and density, among others, in order to enable material and energy recovery. The mechanical processing produced the following material fractions: "Fine fractions <4.5 mm", "Combustibles", "Inert", "Ferrous metals" and "Non-ferrous metals". Further details on the employed mechanical processing and produced fractions are reported by Hernández Parrodi, Raulf, Vollprecht, Pretz, & Pomberger, 2019c. The "Fine fractions <4.5 mm" were further mechanically processed and investigated by Vollprecht, Hernández Parrodi, Lucas, & Pomberger, 2020, while the quality of the extracted "Non-ferrous metals" was studied in Lucas et al., 2019. The recovery of ferrous metals from landfilled material has been successfully carried out in previous investigations (Van Vossen & Prent, 2011; Wagner & Raymond, 2015) and, therefore, the "Ferrous metals" fraction was not further investigated in the MSG case study. Sieving the excavated landfill material into different particle size ranges as a first treatment step, followed by sorting the coarse fractions into different waste types to characterize the material has been addressed in several previous (E)LFM investigations (García Lopez et al., 2019; Hogland, 2002; Hull, Krogmann, & Strom, 2005; Kurian, Esakku, Palanivelu, & Selvam, 2003; Quaghebeur et al., 2013; Stessel & Murphy).

The present study focuses on the obtained "Combustibles" and "Inert" fractions, which are intended to be valorized as an alternative fuel (i.e. refuse derived fuel (RDF)) and a substitute for construction aggregates (e.g. construction gravel), respectively. The main physico-chemical characteristics of each fraction, according to the applicable European Directives (i.e. 2000/76/EC on Incineration of Waste, EN 15359:2011 on Solid Recovered Fuels, 2008/98/EC on Waste and 1999/31/EC on Landfill of Waste) and Austrian ordinances (i.e. Waste Incineration Ordinance (Abfallverbrennungsverordnung – AVV) and Recycling Building Materials Ordinance (Recycling-Baustoffverordnung – RBV)), were determined in the owc and dry states. That information was used to evaluate the quality of the produced fractions in each state and determine their suitability for the intended WtM and WtE valorization routes, as well as to analyze the effects of the owc on the quality of each fraction.

2. MATERIALS AND METHODS

2.1 Site description, excavation works and mechanical pre-processing

The present case study was carried out at the landfill site "Centre d'enfouissement Technique de Mont-Saint-Guibert (CETeM)", which is located in the municipality of MSG, Belgium. This landfill served as one of the main disposal sites of municipal solid waste, non-hazardous industrial waste and construction and demolition waste in the province of Walloon Brabant (Bureau d'études gre-

isch (beg), 2002). The landfilled material was extracted by means of excavators and pre-processed with a ballistic separator (Stadler model STT 6000) directly after excavation. The ballistic separation was performed in two steps: firstly with screen paddles of 200 mm and secondly of 90 mm, from which representative samples were taken for further study. The fine fractions <90 mm of this case study were obtained from the second ballistic separation step and represented around 77 wt.% of the total amount of pre-processed material (~374 Mg). More detailed information about the landfill site, excavation works, mechanical pre-processing, sampling procedures and characteristics of the excavated material can be found in Garcia Lopez et al., 2019 and Hernández Parrodi et al., 2019a.

2.2 Mechanical processing of the Combustibles and Inert fractions

The “Combustibles” and “Inert” fractions were produced with the light and heavy fractions, respectively, which in turn were obtained from the density separation steps of the mechanical processing in the owc and dry states in Hernández Parrodi et al., 2019c. Previous to the density separation steps, the fine fractions <90 mm were subjected to particle size classification and ferrous and non-ferrous metals extraction. The particle size classification steps produced the particle size ranges 90-30 mm, 30-10 mm and 10-4.5 mm. The density separation method applied to those particle size ranges corresponds to windsifting. A cross-flow windsifter was employed in the particle size range 90-30 mm, whereas a zig-zag windsifter was used in the particle size ranges 30-10 mm and 10-4.5 mm. After density separation, both light and heavy fractions were sieved at 4.5 mm in order to remove loosened fine particles (i.e. impurities) throughout the mechanical processing. Subsequently, the heavy fractions were processed with near infrared (NIR) sorting to further extract combustible materials. The extracted combustible materials from the heavy fractions were added to the light fractions for joint valorization and to produce the “Combustibles” fraction. The heavy fractions after further removal of combustible materials were denominated the “Inert” fractions. Further information on the application of NIR sorting to the heavy fractions of the fine fractions <90 mm are reported in Küppers, Hernández Parrodi, Garcia Lopez, Pomberger, & Vollprecht, 2019 and Hernández Parrodi et al., 2019c.

The median values obtained from processing all composite samples of the fine fractions <90 mm (n=16) in the

owc (n=8) and dry (n=8) states were used to elaborate the general mass balance of the mechanical processing, which was reported and analyzed in Hernández Parrodi et al., 2019c.

2.2.1 Combustibles fractions

The general mass balance of the mechanical processing of the fine fractions <90 mm in Hernández Parrodi et al., 2019c reported total amounts of “Combustibles” of 12.5 wt.% in the owc state and 9.0 wt.% in the dry state. In turn, the mass distribution of the “Combustibles” fraction among the particle size ranges 90-30 mm, 30-0 mm and 10-4.5 mm in the owc state was about 4.6 wt.%, 5.0 wt.% and 2.5 wt.%, respectively. In the dry state, the particle size range 90-30 mm presented an amount of 4.1 wt.%, while 30-10 mm accounted for 2.7 wt.% and 10-4.5 mm for 2.0 wt.%. This information is shown as Sankey diagrams in Figure 1.

The physical appearance of each of the particle size ranges of the produced “Combustibles” fractions by the employed mechanical processing in the owc and dry states is displayed in Figure 2. In those images it can be seen that the “Combustibles” fractions were mainly composed of plastics, textiles, wood and paper & cardboard in both states, as well as that the presence of plastics and textiles seems to decrease with particle size. It is also clear that the owc state presents a higher amount of surface defilements (i.e. impurities) than the dry state. Composite samples of each of these fractions were used for the laboratory analyses performed in this study.

2.2.2 Inert fractions

As shown in Figure 3, the “Inert” fractions accounted for 35.5 wt.% of the total amount of produced fractions in the owc state; from which 15.3 wt.%, 15.6 wt.% and 6.3 wt.% corresponded to the particle size ranges 90-30 mm, 30-10 mm and 10-4.5 mm, respectively. In turn, the dry state showed a total amount of 37.2 wt.%, with 15.5 wt.% of the material present in the particle size range 90-30 mm, 13.0 wt.% in 30-10 mm and 8.1 wt.% in 10-4.5 mm.

Figure 4 displays photographs of the “Inert” fractions in the owc and dry states, in which it can be observed that these fractions are mostly comprised of concrete, bricks, stones and glass. The presence of concrete and bricks appears to decrease with particle size in both states. Similarly as for the “Combustibles” fractions, the “Inert” fractions show a greater amount of impurities in the owc state than in the dry state. Composite samples were used to deter-

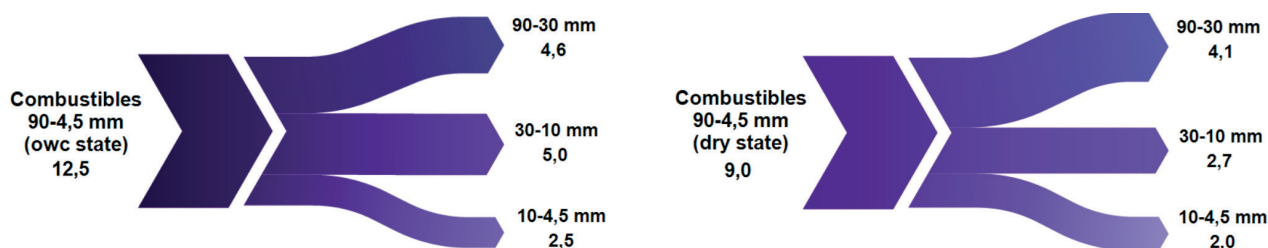


FIGURE 1: Mass distribution of the “Combustibles” fractions among particle size ranges in the owc and dry states [figures in wt.%] (Hernández Parrodi et al. 2019c).



FIGURE 2: “Combustibles” fractions in the owc and dry states (Hernández Parrodi et al. 2019c).

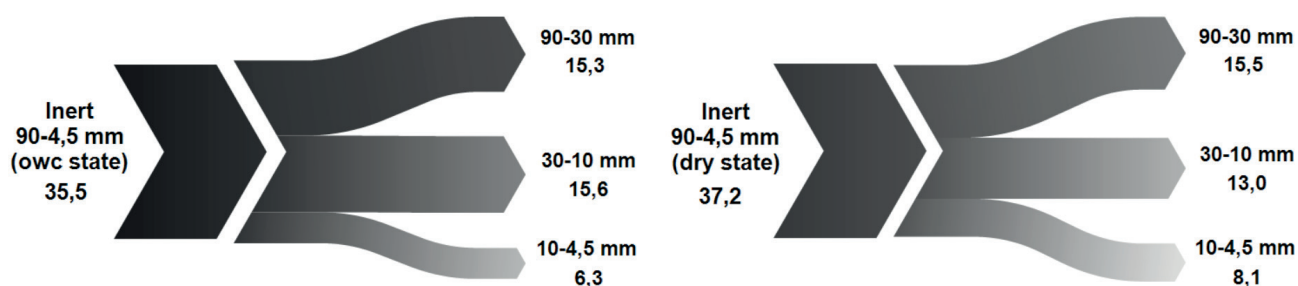


FIGURE 3: Mass distribution of the “Inert” fractions among particle size ranges in the owc and dry states [figures in wt.%) (Hernández Parrodi et al. 2019c).

mine the physico-chemical properties of these fractions as well.

2.3 Laboratory analyses

The determination of the physico-chemical characteristics of the “Combustibles” and “Inert” fractions was performed by the laboratory for environmental analyses of the Chair of Waste Processing Technology and Waste Management (AVAW) of the Montanuniversität Leoben, which is accredited as testing laboratory according to ISO/IEC 17025.

A total of 3 composite samples ($n=3$) of each fraction (i.e. “Combustibles” and “Inert” fractions) of each particle size range (i.e. 90-30 mm, 30-10 mm and 10-4.5 mm) and of each state (i.e. owc and dry states) was analyzed in order to determine the pseudo-total contents (aqua regia digestion), among other parameters, of the “Combustibles” and “Inert” fractions. Additionally, the leachable concentrations of the “Inert” fractions were determined, as leaching tests are useful to determine the susceptibility of the fine fractions to serve alternative purposes (Kaczala et al., 2017). Depending on the reference taken for the limit values to be met, the arithmetic mean and standard error, with

a confidence interval of 95% ($Ci= 95\%$), or the 50th percentile (median) and 80th percentile of the laboratory results were employed to describe each of the analyzed fractions. Box-and-whisker plots were elaborated with the 20th, 50th and 80th percentiles, as well as with the maximum and minimum values.

2.3.1 Laboratory analyses of the Combustibles fractions

Solid matter laboratory analyses were performed to determine the main physico-chemical characteristics of the “Combustibles” fractions, as well as to individually evaluate their suitability for the production of RDF according to the EN 15359:2011 and the AVV. The results of each particle size range were also employed to calculate the physico-chemical characteristics and quality of the mixture of the 3 particle size ranges, in the original proportions in which they were generated by the mechanical processing, as a single particle size range (i.e. 90-4.5 mm). The original proportions in which the “Combustibles” fractions were generated were determined by ponderating the mass distribution of the owc and dry states presented in Figure 1. In the owc state, the median original proportions were about 38 wt.%, 41 wt.% and 21 wt.% of the particle size ranges 90-

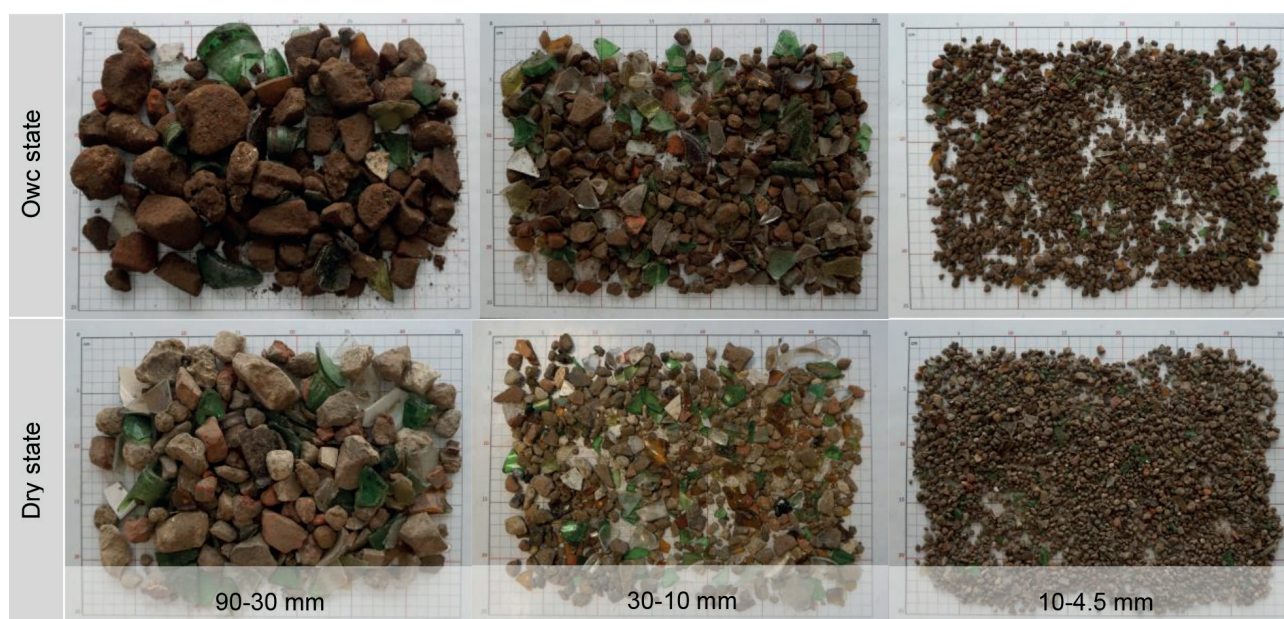


FIGURE 4: "Inert" fractions in the owc and dry states (Hernández Parrodi et al. 2019c).

30 mm, 30-10 mm and 10-4.5 mm, respectively. The median original proportions in the dry state presented amounts of around 47 wt.% for the particle size range 90-30 mm, 31 wt.% for 30-10 mm and 22 wt.% for 10-4.5 mm.

The pseudo-total contents of heavy metals and other elements in the "Combustibles" fractions, as well as of additional parameters (e.g. dry matter (DM) content, net calorific value (NCV) and ash content (AC)), in the owc and dry states were determined according to the European Standard EN 15359:2011 on "Solid Recovered Fuels – Specifications and Classes" and the AVV. In the EU the EN 15359:2011 provides the overarching classification and specifications criteria for the production and utilization of solid recovered fuel (SRF), whereas the Directive on the Incineration of Waste (2000/76/EC) sets the emission limit values for waste (co-)incineration plants. The EN 15359:2011 employs parameters such as NCV, chlorine (Cl) and mercury (Hg) to determine if the material in question can be utilized as SRF and, given that the material meets the specifications, classifies the SRF according to its properties. The classification system of the EN 15359:2011 is shown in Table 1.

In Austria, the production and utilization of RDF (including SRF), as well as the emissions from co-incineration, cement and power plants, are further regulated in the

AVV. This ordinance sets the limit values for the contents of certain heavy metals (i.e. arsenic (As), cadmium (Cd), cobalt (Co), chromium (Cr), mercury (Hg), nickel (Ni), lead (Pb) and antimony (Sb)) in RDF depending on the type of application. Table 2 presents a summary of the limit values of the AVV for the corresponding heavy metals according to utilization type.

The determination of the DM content was done according to the DIN EN 14346 (Process A), while the DIN 51900-1 was followed to determine the NCV. The contents of Cl, fluorine (F), sulfur (S) and bromine (Br) were determined via calorimetric digestion (ÖNORM EN 14582) according to the DIN EN ISO 10304-1. The AC was determined following the ÖNORM EN 15403 and the heavy metals pseudo-total contents were determined through inductively coupled plasma - mass spectrometry (ICP-MS) according to the ÖNORM EN 15411. The total organic carbon (TOC) and polycyclic aromatic hydrocarbons ($\Sigma 16$ PAHs/EPA) contents were determined according to the ÖNORM EN 13137 and the ÖNORM L 1200, respectively.

2.3.2 Laboratory analyses of the Inert fractions

Analogously to the "Combustibles" fractions, the particle size ranges 90-30 mm, 30-10 mm and 10-4.5 mm of the "Inert" fractions in the owc and dry states were subject

TABLE 1: Specifications and classes of SRF according to the EN 15359:2011.

Classification property	Statistical measure	Unit	Classes				
			1	2	3	4	5
NCV	Mean	[MJ/kg (ar)]	≥ 25	≥ 20	≥ 15	≥ 10	≥ 3
Cl	Mean	[wt.% (DM)]	≤ 0.2	≤ 0.6	≤ 1	≤ 1.5	≤ 3
Hg	Median	[mg/MJ (ar)]	≤ 0.02	≤ 0.03	≤ 0.08	≤ 0.15	≤ 0.5
	80 th percentile	[mg/MJ (ar)]	≤ 0.04	≤ 0.06	≤ 0.16	≤ 0.3	≤ 1

Notes: DM= dry matter, ar= as received.

TABLE 2: Limit values for the utilization of RDF according to the AVV.

Parameter	Unit	For use in co-incineration plants		For use in cement plants		For use in power plants ¹⁾	
		Median	80 th percentile	Median	80 th percentile	Median	80 th percentile
As	[mg/MJ (DM)]	1	1.5	2	3	2	3
Cd	[mg/MJ (DM)]	0.17	0.34	0.23	0.46	0.27	0.54
Co	[mg/MJ (DM)]	0.9	1.6	1.5	2.7	1.4	2.5
Cr	[mg/MJ (DM)]	19	28	25	37	31	46
Hg	[mg/MJ (DM)]	0.075	0.15	0.075	0.15	0.075	0.15
Ni	[mg/MJ (DM)]	7	12	10	18	11	19
Pb	[mg/MJ (DM)]	15	27	20	36	23	41
Sb	[mg/MJ (DM)]	7	10	7	10	7	10

Notes: DM= dry matter.

¹⁾ With a contribution of $\leq 10\%$ of the thermal energy from the incineration of waste to the total thermal energy.

to solid matter analyses and, in addition, to leaching tests. The suitability of the “Inert” fractions for the production of a substitute for construction aggregates was evaluated according to the RBV and was performed per particle size range and as a single particle size range mixed in the original proportions in which the particle sizes were generated (only applicable to the solid matter analyses) as well, which were calculated by ponderating the mass distribution of the owc and dry states displayed in Figure 2. In the owc state, the median original proportions of the particle size ranges 90-30 mm, 30-10 mm and 10-4.5 mm corresponded to about 41 wt.%, 42 wt.% and 17 wt.%, whereas in the dry state they accounted for around 42 wt.%, 36 wt.% and 22 wt.%, respectively.

The solid matter analyses and leaching tests were carried out according to the RBV, which establishes the specifications, limit values and quality classes for the reuse and recycling of construction and demolition waste, as well as the allowed applications of such materials in Austria. However, the scope of this ordinance contains an exclusive lists of waste types which may be used for the production of recycled aggregates. Inert materials recovered through (E)LFM are not included in that list. Nevertheless, to this day the EU does not yet have an overarching directive to regulate this type of materials (Saveyn et al., 2014) and, therefore, the RBV was taken as a reference in this study. The RBV employs parameters, such as heavy metals (i.e. As, Cd, Co, Cr, Cu, Hg, Ni, Pb, and Zn), hydrocarbon index (KW index) and $\Sigma 16\text{PAHs/EPA}$ content, in the solid matter to determine if the material in question is suitable to replace construction aggregates in certain applications, which are also defined in the same ordinance. As for the leaching tests, that ordinance sets the limit values for parameters such as pH, electric conductivity, TOC, KW index, Co, Cr, Cr, molybdenum (Mo), Ni, ammonium-N (NH_4^+), chloride (Cl^-), nitrite (NO_2^-), sulfate (SO_4^{2-}) and the methylene blue active substance assay (MBAS assay), among others. A synopsis of the classification system of the RBV for both solid matter and leachate analyses is presented in Table 3. The allowed applications of each of the quality classes in Table 3 are defined in the RBV as well, which are shown in Table 4.

Regarding the solid matter analyses, the S content of the “Inert” fractions was determined via inductively coupled plasma - optical emission spectrometry (ICP-OES) according to the ÖNORM EN ISO 11885. The concentrations of the heavy metals and other elements were determined via inductively coupled plasma - mass spectrometry (ICP-MS) and aqua regia digestion (ÖNORM EN 13657 (6.3)) according to the ÖNORM EN ISO 17294-2. For the determination of the KW index the ÖNORM EN 14039 was followed. Loss on ignition (LOI) was determined according to the DIN EN ISO 26845:2008-06 at 1025°C, deviating from the standard as individual determination. The chemical composition was determined through quantitative x-ray fluorescence (XRF) according to the DIN EN ISO 12677. DM, TOC and $\Sigma 16\text{PAHs/EPA}$ contents were determined analogously to the “Combustibles” fractions.

As for the leaching tests, pH was determined according to the ISO 10523, while the DIN EN 27888 was used for the determination of the electric conductivity. The concentrations of Cl^- , NO_2^- , SO_4^{2-} and fluoride (F^-) were determined following the DIN EN ISO 10304-1 and NH_4^+ was determined according to the DIN 38406-5. The ÖNORM EN 903 was followed for the MBAS assay, whereas TOC and KW index were determined according to the DIN EN 1484-3 and the EN ISO 9377-2, respectively. The concentrations of Co, Cr, Cr, Mo and Ni were determined via leaching tests (ÖNORM EN 12457-4 (waste)) according to the ÖNORM EN ISO 17294-2 (ICP-MS).

3. RESULTS AND DISCUSSION

3.1 Combustibles fractions

The results of the solid matter laboratory analyses of the “Combustibles” fractions for the parameters NCV, AC, Cl, F, S, Br, C, H, Hg and N, as well as DM, TOC and $\Sigma 16\text{PAHs/EPA}$ contents, per particle size range (i.e. 90-30 mm, 30-10 mm, 10-4.5 mm and 90-4.5 mm (mixed in original proportions)) and state (i.e. the owc and dry states) are presented in Table 5.

The figures in Table 5 show that the DM content in the owc state, which was set prior to the experiments to 85.0 wt.%, varied between 86.7 wt.% and 74.5 wt.% among the particle size ranges and presented a tendency to decrease towards finer particle sizes. The dry state showed a varia-

TABLE 3: Limit values for the recycling of construction materials according to the RBV.

Parameter	Unit	Quality classes			
		U-A	U-B	U-E	H-B
Leaching tests (L/S 10)	pH	7.5 ¹⁾ - 12.5 ²⁾			
	Electric conductivity	150			
	Cr _{Tot}	0.6	1	0.6	1
	Co	-	-	1	-
	Cu	1	2	1	2
	Mo	-	-	0.5	-
	Ni	0.4	0.6	0.4	-
	NH ₄ ⁺	4	8	4	8
	Cl ⁻	800	1,000	800	1,000
	NO ₂ ⁻	-	2	-	-
	SO ₄ ²⁻	2,500	6,000	2,500	6,000
	TOC	100	200	100	200
	KW index	-	-	5	-
	MBAS assay	-	-	1	-
Solid matter	As	-	-	50 / 200 ⁴⁾	-
	Pb	150	-	150 / 500 ^{3), 4)}	-
	Cd	-	-	2 / 4 ⁴⁾	-
	Cr _{Tot}	90 / 300 ⁴⁾	90 / 700 ⁴⁾	300 / 700 ⁴⁾	90 / 700 ⁴⁾
	Co	-	-	50	-
	Cu	90 / 300 ⁴⁾	90 / 500 ⁴⁾	100 / 500 ⁴⁾	90 / 500 ⁴⁾
	Ni	60 / 100 ⁵⁾	60	100	60
	Hg	0.7	-	1 / 2 ⁴⁾	0.7
	Zn	450	-	500 / 1,000 ⁴⁾	450
	KW index	150	200	150	200
	Σ16PAHs/EPA	12	20	12	20

Notes: DM= dry matter.

¹⁾ For natural non-contaminated rock the pH-range starts from 6.5.

²⁾ If the pH value and/or the electrical conductivity are exceeded, freshly broken concrete containing recycling building materials can be subjected to rapid carbonation based on the ÖNORM S 2116-3 "Investigation of Stabilized Waste, Part 3: Rapid Carbonation", issued on January 1, 2010. In this case, the eluate must be examined again. In any case, the limit values must be observed after carbonation. This applies to both the pH value and electrical conductivity.

³⁾ If the Pb content exceeds 150 mg/kg (DM), the Pb concentration in the eluate must be determined and a limit value of 0.3 mg/kg (DM) must be complied with.

⁴⁾ The higher limit value applies if background concentrations can be demonstrated.

⁵⁾ No limit value applies if background concentrations can be demonstrated.

tion of the DM content between 97.3 wt.% and 97.1 wt.% among the particle size ranges, which also presented a decreasing tendency (albeit very slight) towards finer particle sizes. This can be explained by the greater presence of impurities in the owc state than in the dry state, which tend to absorb/adsorb water and whose amount has also shown an increasing trend with the decrease in particle size. Furthermore, this information reveals that the material processed in the dry state with an initial DM content of 100.0 wt.% absorbed/adsorbed between 2.7 wt.% and 2.9 wt.% of moisture from the environment along the mechanical processing, which suggests that a closed moisture-free mechanical processing would be needed to maintain the water content below those levels. The calculated DM contents of the mixed single particle size range 90-4.5 mm accounted for 80.3 wt.% in the owc state and 97.2 wt.% in the dry state.

The NCV was significantly higher in the dry state than in the owc state although it was normalized to DM. This means that either during mechanical processing in the owc state calorific materials were lost to the fine fractions <4.5 mm or inert materials were lost to the same fraction during processing in the dry state. It is suggested that the latter is the case, i.e. inorganic materials remained attached to the calorific fractions in the owc state to a greater extent than in the dry state. The NCV was higher for coarser fractions, i.e. combustibles occurred rather in coarser particle size, and varied from 15.8 MJ/kg (DM) to 7.9 MJ/kg (DM) in the owc state and from 17.6 MJ/kg (DM) to 8.9 MJ/kg (DM) in the dry state. As a mixed single particle size range, the NCV of the "Combustibles" fractions accounts for 12 MJ/kg (DM) in the owc state and 14.4 MJ/kg (DM) in the dry state. The values of the NCV referring to the original substance (as received (ar)) are in the range of those us-

TABLE 4: Permitted use of recycled construction aggregates per quality class according to the RBV.

Class	Description	Unbound application ¹⁾ without low permeable, bound top layer or base layer	Unbound application ¹⁾ under low permeable, bound top layer or base layer	Production of concrete from the strength class C 12/15 on or strength class C 8/10 from the exposure class XC1 on	Production of asphalt
U-A	Aggregates for the unbound use, as well as for the hydraulic or bituminous bound use	Yes	Yes	Yes	Yes
U-B	Aggregates for the unbound use, as well as for the hydraulic or bituminous bound use	No	Yes ²⁾	Yes	Yes
U-E	Aggregates for the unbound use, as well as for the hydraulic or bituminous bound use	Yes ^{2), 3)}	Yes ²⁾	Yes	Yes
H-B	Aggregates exclusively for the production of concrete from the strength class C 12/15 on or from the strength class C 8/10 from the exposure class XC1 on	No	No	Yes	No

Notes:

¹⁾ Including manufacture of concrete under strength class C 12/15 or up to strength class C 8/10 under exposure class XC1.

²⁾ Use according to § 13 Z1 (unless a water-legal license for the use of recycled building materials is not available in protected areas, not in designated zones of sanctuaries, not in designated protected areas, not in and immediately above groundwater and not in surface water).

³⁾ Only in the trapezoid of the track body as a base layer (§ 13 Z 4).

able in fluidized bed incinerators (Sarc & Lorber, 2013) for the particle size ranges 90-30 mm and 30-10 mm, but below that range for the particle size range 10-4.5 mm. The ranges of NCV values of the "Combustibles" fractions are in the same range as those obtained for individual calorific fractions in a previous LFM project in Austria (Wolfsberger et al., 2015).

The AC is significantly higher for the samples processed in the owc state than for those processed in the dry state. This is associated with the presence of a larger amount of surface defilements in the owc state and the predominant inorganic nature of surface defilements. Contrary to the NCV, the AC of the "Combustibles" fractions increased with the decrease in particle size, which can also be explained by the increase in the amount of impurities as particle size decreased and the directly proportional correlation between the amount of impurities composed predominantly of inorganic compounds and the AC. In the dry state the AC reached values above 50 wt.% (DM) in the particle size range 10-4.5 mm, while it did as well in the particle size ranges 30-10 mm and 10-4.5 mm in the owc state. Amounts of 47.4 wt.% (DM) and 38.2 wt.% (DM) of AC were calculated for the mixed single particle size range 90-4.5 mm in the owc and dry states, respectively. The AC values of the "Combustibles" fractions were in the range of low quality supplier materials for RDF production from municipal solid waste and industrial or commercial waste (Sarc & Lorber, 2013), which show that the quality of the combustible materials obtained through LFM for the production of RDF might not be very far from that of more recent types of waste.

The Cl and S concentrations in the "Combustibles" fractions decreased with decreasing particle size in both the owc and dry states. As a mixed single particle size range, the concentrations of Cl and S are in the range of 0.9-1.2 wt.% and 0.5-0.6 wt.%, respectively, for both states; which is in agreement with commercial RDF (Sarc & Lorber, 2013). The determined concentrations were higher for the material processed in the dry state, which suggests that Cl and S are

enriched in combustible materials (e.g. as PVC for Cl and vulcanized plastics for S) and not in inorganic surface defilements. The F and B concentrations were insignificant. The C contents decreased with decreasing particle size in both the owc and dry states, and were higher for the fractions treated in the dry state, which suggests dominance of organic carbon. This can be confirmed by the TOC values, which indicated that practically the entire C content is organic. Amounts of 33.0 wt.% (DM) and 39.7 wt.% (DM) account for the C content of the mixed single particle size range in the owc and dry states, respectively. The H content showed the same tendency as Cl, S and C contents, both with respect to particle size and processing state, which suggests its presence in combustible materials. H presented concentrations in the range of 2.9-5.8wt.% (DM) in the owc state and 3.2-6.8 wt.% (DM) in the dry state. For N, which showed respective concentrations in the range of 1.0-2.0 wt.% (DM) and 0.9-1.4-wt.% (DM) in the owc and dry states, a decrease with decreasing particle size was observed; but not clear correlation with the processing state (i.e. owc and dry states) was identified. The concentrations of $\Sigma 16\text{PAHs/EPA}$ were in the range of 10.9-13.3 mg/kg (DM) in the owc state and 9.4-13.4 mg/kg (DM) in the dry state, and did not seem to be influenced by the processing state and are highest for the intermediate particle size range (i.e. 30-10 mm) in both states. As for the Hg concentrations, no significant variations between the owc and dry states for the particle size ranges 90-30 mm and 10-4.5 mm were shown. The particle size range 30-10 mm presented the highest concentrations of Hg in the owc state, while 10-4.5 mm did so in the dry state. The concentrations of Hg ranged from 0.06-0.30 mg/MJ (ar) in the owc state and from 0.07-0.20 mg/MJ (ar) in the dry state. The Hg concentrations are rather enriched in the finer particle size ranges, which suggests its association with surface defilements.

The pseudo-total contents of the heavy metals As, Cd, Co, Cr, Hg, Ni, Pb and Sb in the "Combustibles" fractions per particle size range and state, and as a single particle size range mixed in the original proportions of each particle

TABLE 5: Laboratory results of the solid matter analyses of the “Combustibles” fractions.

Parameter	Unit	90-30 mm				30-10 mm				10-4.5 mm				90-4.5 mm (mixed in original proportions)			
		Owc		Dry		Owc		Dry		Owc		Dry		Owc		Dry	
		Mean	Std. error	Mean	Std. error	Mean	Std. error	Mean	Std. error	Mean	Std. error	Mean	Std. error	Mean	Std. error	Mean	Std. error
DM	[wt.% (ar)]	86.70	1.69	97.27	0.83	77.17	1.90	97.20	0.11	74.53	0.43	97.13	0.07	80.24	0.81	97.22	0.41
NCV ¹⁾	[MJ/kg (DM)]	15.80	0.41	17.60	1.63	10.53	0.95	13.40	1.13	7.87	1.24	8.93	0.24	11.97	0.48	14.39	0.90
	[MJ/kg (ar)]	13.40	0.71	17.07	1.49	7.60	0.98	12.93	1.08	5.23	0.91	8.57	0.26	9.31	0.43	13.92	0.82
AC	[wt.% (DM)]	33.00	4.21	26.10	0.97	52.87	1.12	42.70	1.93	62.70	4.28	57.70	1.41	47.38	1.37	38.20	1.26
Cl	[wt.% (DM)]	1.48	1.16	1.91	0.69	0.63	0.16	0.73	0.28	0.16	0.01	0.16	0.01	0.86	0.47	1.16	0.37
F	[wt.% (DM)]	0.02	0.00	0.02	0.00	0.02	0.00	0.02	0.00	0.02	0.00	0.02	0.00	0.02	0.00	0.02	0.00
S	[wt.% (DM)]	0.58	0.29	0.74	0.12	0.46	0.07	0.40	0.02	0.41	0.04	0.38	0.03	0.50	0.12	0.55	0.04
Br	[wt.% (DM)]	0.02	0.00	0.02	0.01	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	-	-	-	-
C	[wt.% (DM)]	42.53	6.67	49.17	2.65	29.83	1.54	35.93	1.88	21.83	0.66	24.67	0.73	32.98	2.41	39.67	1.39
H	[wt.% (DM)]	5.82	1.05	6.80	0.75	3.84	0.18	4.53	0.22	2.90	0.08	3.18	0.05	4.40	0.35	5.30	0.39
N	[wt.% (DM)]	1.99	2.00	1.40	0.49	1.04	0.08	1.23	0.23	0.97	0.03	0.94	0.04	1.39	0.78	1.24	0.15
TOC	[wt.% C (DM)]	43.37	5.35	52.13	2.58	28.40	2.01	37.57	2.69	18.97	1.52	20.60	2.16	32.11	1.54	40.68	2.45
Σ16PA Hs/EPA	[mg/kg (DM)]	10.89	12.77	9.38	4.79	21.33	19.45	18.23	5.87	13.27	2.68	13.40	3.42	15.67	5.21	13.01	4.15
Parameter	Unit	Median	80 th percentile	Median	80 th percentile	Median	80 th percentile	Median	80 th percentile	Median	80 th percentile	Median	80 th percentile	Median	80 th percentile	Median	80 th percentile
Hg	[mg/MJ (ar)]	0.06	0.07	0.07	0.09	0.30	0.31	0.11	0.11	0.20	0.23	0.20	0.24	0.15	0.16	0.09	0.11
Ba	[mg/MJ (DM)]	61.39	239.49	21.02	22.05	112.97	218.92	66.42	83.88	136.02	147.46	102.99	103.66	89.94	217.66	42.38	49.18
Be	[mg/MJ (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Cu	[mg/MJ (DM)]	7.59	20.13	14.20	51.36	18.99	24.68	11.19	40.75	25.42	30.76	27.99	30.00	17.41	20.92	29.89	42.45
Mo	[mg/MJ (DM)]	0.89	0.92	0.57	0.64	0.52	0.62	0.37	0.38	0.92	1.09	0.88	1.09	0.81	0.82	0.55	0.57
Mn	[mg/MJ (DM)]	13.92	16.20	7.95	8.98	26.58	27.72	19.40	19.40	40.68	42.20	33.58	33.58	21.50	23.67	14.11	15.09
Se	[mg/MJ (DM)]	<d.l.	-	<d.l.	-	0.25	0.27	<d.l.	-	0.42	0.43	0.03	0.39	-	-	-	-
Tl	[mg/MJ (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
V	[mg/MJ (DM)]	0.82	1.09	0.63	0.76	2.28	2.79	1.12	1.39	3.56	3.64	2.69	2.75	1.66	2.03	1.18	1.18
Zn	[mg/MJ (DM)]	77.22	92.41	56.82	62.27	131.96	132.53	163.43	178.66	179.24	186.10	150	153.36	112.43	112.54	102.09	103.89

Notes: <d.l. = amount below detection limit. ar= as received. DM= dry mass. n=3, std. error with Ci of 95%.¹⁾ The gross calorific value (GCV) was determined experimentally according to the DIN 51900-1. A fixed correction factor of f= 0.92, based on the GCV, was used for the calculation of the NCV according to the “AQS Richtlinie (2001)”.

size range are shown in the form of box-and-whisker plots in Figure 5.

The data in Figure 5 show that the concentrations of As, Cd, Co, Ni and Pb increase with decreasing particle size, which suggests that they are present in the inorganic defilements or adsorbed to their surfaces. For Cr, Hg, and Sb this trend is less pronounced. For As, Cd, Co, and mostly Pb and Ni, concentrations in the owc state processed samples are higher than in those processed in the dry state, which confirms their association with inorganic defilements.

Cr concentrations in the coarsest particle size range are higher for the material processed in the dry state, whereas in the finer particle size ranges they are higher for those materials processed in the owc state. This suggests that one part of Cr is present in larger particles, e.g. textiles due to tanning agents, whereas another part is present in fine-grained surface defilements.

After comparing the results with the limit values set in the AVV (Table 2), it was observed that the concentrations of the particle size range 90-30 mm in the owc state exten-

sively complied with the limit values of all heavy metals for use in power plants; except Pb, which was only exceeded for the 80th percentile by a minuscule amount. In turn, the same particle size in the dry state presented low concen-

trations of all heavy metals as well, failing only to comply with the median and 80th percentile limit values for Cd for use in power plants by small amounts. However, the median concentrations of Hg in the owc and dry states were

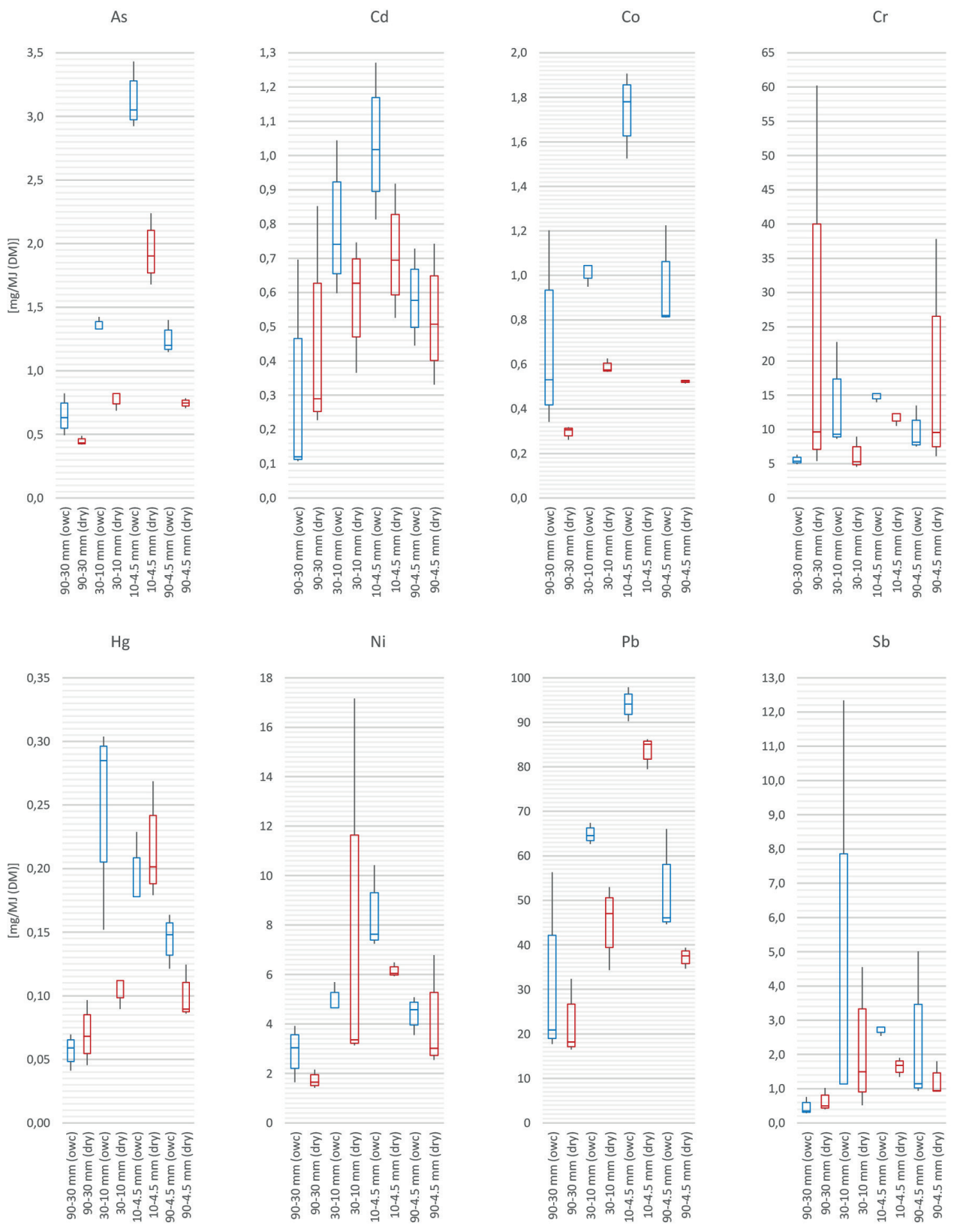


FIGURE 5: Heavy metals concentrations of the "Combustibles" fractions in the owc (blue) and dry (red) states.

close to that of the limit value and, hence, this element could also be problematic. The particle size range 30-10 mm failed to comply with the limit values of Cd and Pb for both median and 80th percentile in the owc and dry states. Additionally, that particle size range exceeded the median and 80th percentile limit values of Hg in the owc state, while in the dry state only the limit value for the median was exceeded. The concentrations of Cd, Hg and Pb of the particle size range 10-4.5 mm were above the limit values for the median and 80th percentiles in both owc and dry states. In the owc state, the concentration of As exceeded the median and 80th percentile limit values, while the median concentration of Co was above the limit value as well.

According to the previous data, it can be said that the quality of the "Combustibles" fractions tends to decrease with particle size. That can be explained by the presence of heavy-metal bearing fine-grained particles. If the particle size ranges 90-30 mm, 30-10 mm and 10-4.5 mm were to be mixed in the original proportions, the resulting single particle size range 90-4.5 mm of the "Combustibles" fractions would exceed the median and 80th percentile limit values for Hg and Pb in the owc state, while the median for Cd would also be above the limit value. In the dry state, the particle size range 90-4.5 mm would exceed the median and 80th percentile limit values of Cd, as well as the median limit values of Hg and Pb.

3.1.1 Valorization of Combustibles fractions as RDF

Previous investigations have shown that plastics from (E)LFM are most likely not suitable for recycling routes and, thus, their valorization should be directed to energy recovery through thermochemical processes, such as incineration, pyrolysis and gasification, or to the production of monomers and industrial chemical precursors (Canopoli, Fidalgo, Coulon, & Wagland, 2018). This might be the case, since LFM plastic waste is commonly characterized by its high ash, impurities and heavy metals contents (Canopoli et al., 2018).

In general, the "Combustibles" fractions recovered in the present case study could be valorized as SRF in (co-) incineration, power and cement plants in the EU, under certain circumstances depending on the type of plant and given that the corresponding plant complies with the applicable emission limit values established in the Directive on the Incineration of Waste (2000/76/EC), since the recovered "Combustibles" fractions meet the specifications set in the EN 15359:2011, in both the owc and dry states. Furthermore, the "Combustibles" fractions could be valorized mixed in one single particle size range (i.e. 90-4.5 mm) in their original proportions (i.e. 38 wt.% of 90-30 mm, 41 wt.% of 30-10 mm and 21 wt.% of 10-4.5 mm in the owc state; 47 wt.% of 90-30 mm, 31 wt.% of 30-10 mm and 22 wt.% of 10-4.5 mm in the dry state) or individually, separated in the particle size ranges of the mechanical processing (i.e. 90-30 mm, 30-10 mm and 10-4.5 mm). The latter approach is reasonable for those cases in which the coarser fraction can be incinerated at a lower price, or even for revenue, in co-incineration plants and only the finer fractions need to be incinerated at higher prices in incineration plants. Altogether, the "Combustibles" fractions corresponded to a

SRF of class-code NVC 5; CI 3; Hg 3 in the owc state and of NVC 4; CI 4; Hg 3 in the dry state. Individually, the particle size range 90-30 mm corresponds to a SRF of class-code NVC 3; CI 4; Hg 3, 30-10 mm to a class-code of NVC 5; CI 2; Hg 5 and 10-4.5 mm to one of NVC 5; CI 1; Hg 4 in the owc state. In the dry state, the particle size ranges 90-30 mm, 30-10 mm and 10-4.5 mm correspond to SRF of class-codes: NVC 3; CI 5; Hg 3, NVC 4; CI 3; Hg 3 and NVC 5; CI 1; Hg 4, respectively. Nevertheless, it is important to stress that legislation on waste may vary from country to country in the EU and additional restrictions, as well as stricter limit values can be applied. It is also relevant to note that the recovered combustible fractions from the fine fractions are likely to be valorized together with those recovered from the coarse fractions (i.e. the 2D >200 mm and 2D 200-90 mm fractions in the MSG case study), which might have a significant positive impact on the quality of the whole recovered combustible fraction, since the combustible fractions recovered from the coarse fractions of (E)LFM frequently present higher NCVs and lower amounts of organic and inorganic pollutants, and account for a considerable share of the processed material.

Some of the circumstances previously mentioned are that not all classes of SRF are suitable for all types of plants (refer to CEN / TR 15508). For example, if cement and lime kilns and power plants use 100% SRF as fuel and have an emission limit of Hg of 0.05 mg/m³, only SRF class Hg 1 is suitable for those plants. SRF with a class Hg 5 could only be used in those plants if this class of SRF represents less than 100% of the fuel mixture. For other SRF classes, the specific transfer factor for a given process and the proportion of SRF determine which classes can be used without improving the transfer conditions. Examples of transfer factors for existing processes are given in the CEN / TR 15508. Additionally, SRF should not be used as fuel if less heat energy is generated and available for the plant-related process, than is consumed during the combustion of the SRF and, therefore, is not available for the process. As a result, for example, the use of SRF class NCV 5 in systems that require a higher minimum heating value for energy production should be avoided.

However, in Austria, where regulations are stricter than in many other EU countries, the "Combustibles" fractions would need to be subjected to a cleaning process, in which the amount of surface defilements and impurities could be further reduced, in order to be valorized as RDF in co-incineration plants.

An alternative to both further cleaning for subsequent co-incineration and direct incineration is the use of pyrolysis and gasification as thermo-chemical valorization methods for the combustible fractions of landfill-mined material in order to produce syngas. Subsequently to the pyrolysis/gasification process, the molten ash residue is vitrified; producing a glassy slag. This is the principal approach in the NEW-MINE project, which proposes the utilization of plasma gasification as alternative thermo-valorization method for the high calorific fractions from landfill-mined waste. The plasma gasification investigated in the NEW-MINE project can cope with RDF materials with higher inorganic pollutant contents, since those pollutants can be immobilized in the

vitrified residue. The gasification process of SRF from municipal solid waste and industrial waste was studied in Zaini, Yang, & Jönsson, 2017; whereas the pyrolysis/gasification of RDF from landfill-mined waste was successfully tested in Zaini, García López, Pretz, Yang, & Jönsson, 2019 on a laboratory scale. It has also been demonstrated that thermal treatment of the glassy slag yielded glass-ceramics with very low leaching of Cr, Cu, Co, Cd and Ni (Rabelo Monich et al., 2020), as well as that inorganic polymer binders can be produced from the (semi)vitreous material obtained as by-product in plasma gasification of waste materials (Ascensão et al., 2019; Machiels et al., 2017). Both glass-ceramics and inorganic polymers are higher value-added products that could be used to replace raw materials in construction applications, such as tiles, bricks and glass foams (Monich et al., 2018; Rabelo Monich, Dogrul, Lucas, Friedrich, & Bernardo, 2019; Rincón, Marangoni, Cetin, & Bernardo, 2016), as well as in the production of concrete (Ascensão et al., 2019; Machiels et al., 2017). Therefore, in contrast to conventional (co-)incineration, plasma gasification might offer a potential WtE valorization route for the combustible fractions obtained from the fine fractions of landfill-mined waste, which in the present case study accounted for 12.5 wt.% and 9.0 wt.% of the total amount of the fine fractions <90 mm in the owc and dry states, respectively.

3.2 Inert fractions

The chemical composition of the “Inert” fractions per particle size range (i.e. 90-30 mm, 30-10 mm, 10-4.5 mm) and state (i.e. the owc and dry states) was determined through XRF analyses. This information is displayed graphically in the form of stacked columns in Figure 6.

The information in Figure 6 unveils that most of the “Inert” fractions was composed of silicon dioxide (SiO_2), followed by aluminium oxide (Al_2O_3), calcium oxide (CaO), iron oxide (Fe_2O_3) and sodium oxide (Na_2O). Chemically, there are no significant differences between the samples processed in the owc state and those processed in the dry state. The LOI was higher for the finest particle size ranges, as moisture is mainly adsorbed by finer particles. Al_2O_3 and CaO concentrations do not significantly change among particle size ranges, whereas Fe_2O_3 increased with the decrease in particle size. This can be explained by the formation of iron hydroxides in the landfill due to the oxidation of Fe^{2+} to Fe^{3+} in the leachate and also by the corrosion of iron particles. A similar behavior is observed for Mn, which is explained analogously by the precipitation of Mn hydroxides due to the oxidation of $\text{Mn}^{2+}/\text{Mn}^{3+}$ to Mn^{4+} . As Cr showed a similar tendency, it is suspected that Cr formed secondary Cr(III) phases as described in Sedlazeck, Höllen, Müller, Mischitz, & Gieré, 2017. Contrary as for Fe and Mn, the higher valent form of Cr was more soluble than the lower valent form.

Additionally, solid matter laboratory analyses were performed to the “Inert” fractions for parameters such as S, C, KW index, N and certain heavy metals (i.e. Cr, Co, Ni, Cu, Zn, As, Cd, Hg and Pb), as well as DM, $\Sigma 16\text{PAHs/EPA}$ and TOC

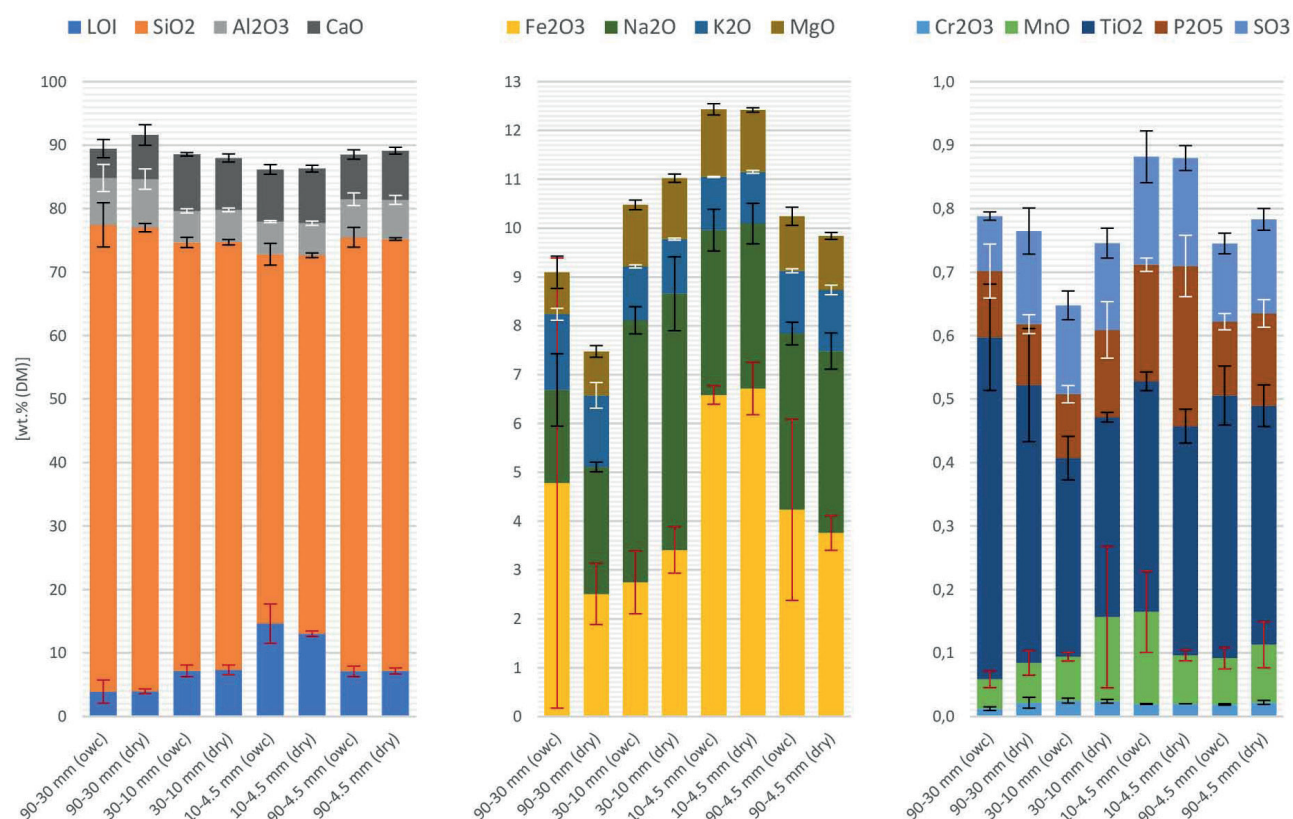


FIGURE 6: Chemical composition of the “Inert” fractions from XRF analyses in the owc and dry states.

contents, per particle size range and state. Table 6 presents a summary of the results of those laboratory analyses.

The results in Table 6 show that the particle size range 90-30 mm presented the best quality among all particle size ranges in both the owc and dry states, complying with all solid matter parameters for all quality classes (i.e. U-A, U-B, U-E and H-B from Table 3); except for the concentration of Pb in the dry state, which was slightly exceeded for all quality classes. However, the standard error of this parameter significantly exceeds the mean value itself and shows the strongest variation among all parameters for that state; suggesting the presence of outliers. Moreover, the amount of Pb was significantly exceeded in the particle size range 10-4.5 mm in both states, whereas the particle size range 30-10 mm complied with the limit value for all quality classes in both states as well. The concentration of Pb in the leaching tests of the "Inert" fractions as a mixed single particle size range 90-4.5 mm can be expected below 0.3 mg/kg (DM) in both states, since the highest concentration determined from all samples of all particle size ranges was 0.26 mg/kg (DM) (Table 7), which was one order of magnitude above those of all other samples. Provided that background concentrations of Pb in the site of application can be proven, a limit value of 500 mg/kg DM would apply to these fractions and, hence, all particle size ranges, except 10-4.5 mm in the dry state, would meet the limit value for all quality classes.

In terms of quality, the particle size range 30-10 mm followed 90-30 mm. In the dry state, the particle size range 30-10 mm complied with all parameters for all quality classes; except for the hydrocarbons content (KW index), which slightly exceeded the limit values for the quality classes U-A and U-E. In the owc state, this particle size range exceeded the limit values for hydrocarbons content for all quality classes, in which classes U-B and H-B were only slightly exceeded. The concentration of Cd in this particle size range exceeded the lower limit value for quality class U-E and presented the same value as the higher limit value (applicable if background concentrations can be demonstrated) in the owc state. However, the standard error of the Cd content in that state suggests outliers and, in addition, Cd content is not relevant for classes U-A, U-B and H-B. The Zn concentration was also exceeded by this particle size range in the owc state for classes U-A, U-B and H-B, as well as the lower limit value for class U-E; meaning that if background concentrations of Zn can be proven, the higher limit value for class U-E would not be exceeded.

The particle size range 10-4.5 mm showed the lowest quality, since the limit values for hydrocarbons, Zn, Cd and Pb were exceeded for all quality classes in both the owc and dry states. No significant differences were identified between the quality of both states in this particle size range; except for Pb, which presented a higher concentration in the dry state.

As a mixed single particle size range 90-4.5 mm, the "Inert" fractions would slightly exceed the limit values for hydrocarbons for the quality classes U-B and H-B in both owc and dry states, while the concentration of Pb would exceed the limit value for class U-A and the lower limit value for classes U-B, U-E and H-B only in the dry state. In the owc

state, the Zn content would exceed quality classes U-A, U-B and H-B, and the lower limit value of class U-E.

In general, it can be said that the dry state presented higher concentrations of Pb; nevertheless, a conclusive tendency cannot be confirmed due to the presence of outliers. In turn, the owc state showed consistently higher contents of hydrocarbons and Zn, which can be explained by the presence of impurities. For Cd no trend could be identified between both states.

The previous information reveals that the quality of the "Inert" fractions, in terms of the solid matter parameters analyzed, decreased with the decrease in particle size. This suggests that the quality decrease is associated with the presence of organic and inorganic impurities and, therefore, a cleaning step would be needed to reduce the concentrations of the problematic elements and compounds (especially those of hydrocarbons), and enable the utilization of the "Inert" fractions as substitute for construction aggregates in Austria. The elevated concentrations of Cd and Pb could be due to the presence of glass, since such elements have been commonly used in glass production as coloring and decorative agents in the past. Hence, the separation of glass from the "Inert" fractions, through a density separation or sensor-based sorting method, might reduce the concentrations of Cd and Pb.

In addition to the solid matter laboratory analyses, leaching tests were performed to samples of the "Inert" fractions according to the RBV. The results of the leaching tests are summarized in Table 7. After comparing the leaching tests parameters of the "Inert fractions" in Table 7 with the corresponding limit values set in the RBV, it was observed that the contents of NH_4^+ significantly exceeded the limit values in almost every case; only the particle size range 30-10 mm in the owc state complied with the limit value of classes U-B and H-B, and exceeded the limit value of classes U-A and U-E by a minuscule amount. High concentrations of NH_4^+ in landfills are in agreement with previous observations (Vollprecht, Frühauf, Stocker, & Ellersdorfer, 2019). Only with one exception, for the particle size range 90-30 mm, the amounts of NH_4^+ were lower in the owc state than in the dry state.

The amounts of anionic surfactants determined by the MBAS assay, which are the active washing components of products such as soap or detergent, were very slightly above the limit values in the particle size ranges 30-10 mm in the owc state and 10-4.5 mm in both states, whereas the amounts in the particle size ranges 30-10 mm in the dry state and 90-30 mm in both states were below the detection limit. It should be noted that the limit value in the RBV for this parameter corresponds to the detection limit of the assay and, therefore, the measured amounts could correspond to outliers.

The pH value of the particle size range 10-4.5 mm in the owc state was very slightly below the limit value of quality classes U-A, U-B and U-E; however, this fraction is suitable for quality class H-B. Hence, pH is not regarded as a problematic parameter in this fraction.

The TOC content of the particle size range 10-4.5 mm in the dry state complied with the limit values for quality classes U-B and H-B, but slightly exceeded those of class-

TABLE 6: Laboratory results of the solid matter analyses of the “Inert” fractions.

Parameter	Unit	90-30 mm				30-10 mm				10-4.5 mm				90-4.5 mm (mixed in original proportions)			
		Owc		Dry		Owc		Dry		Owc		Dry		Owc		Dry	
		Mean	Std. error	Mean	Std. error	Mean	Std. error	Mean	Std. error	Mean	Std. error	Mean	Std. error	Mean	Std. error	Mean	Std. error
DM	[wt. %]	97.13	0.66	99.67	0.13	97.13	0.69	99.73	0.07	90.73	0.07	99.30	0.00	96.05	0.54	99.61	0.05
S	[mg/kg (DM)]	740.00	239.52	1,043.33	252.36	1,176.67	73.63	853.33	34.57	1,966.67	42.84	1,563.33	96.24	1,131.93	95.19	1,089.33	129.87
C	[wt. % (DM)]	1.42	0.45	1.47	0.06	3.33	0.74	3.66	0.48	6.24	0.39	6.32*	0.04	3.04	0.26	2.86	1.09
KW index	[mg/kg (DM)]	60.67	25.44	38.00	31.38	226.67	51.03	164.33	144.28	646.67	183.98	630.00	244.80	230.01	21.98	213.72	13.48
N	[wt. % (DM)]	0.15	0.01	0.14	0.01	0.20	0.01	0.21	0.02	0.35	0.04	0.33	0.05	0.20	0.00	0.21	0.01
Σ16PAHs/ EPA	[mg/kg (DM)]	0.25	0.43	1.70	2.27	0.68*	0.34	0.34*	0.44	3.35	0.76	8.59	6.23	0.86	0.38	2.68	1.66
TOC	[wt. % C (DM)]	0.27	0.08	0.26	0.04	1.60	0.49	2.25	0.61	4.56	0.36	4.85	0.19	1.56	0.18	1.99	0.19
Li	[mg/kg (DM)]	3.47	1.31	4.23	0.77	4.07	0.17	3.83	0.58	8.90	2.19	7.33	1.25	4.64	0.23	4.77	0.60
Be	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Na	[mg/kg (DM)]	1,356.67	329.98	1,256.67	297.32	2,250.00	1,017.75	1,836.67	136.42	1,650.00	152.24	1,640.00	167.46	1,781.73	493.43	1,549.80	136.99
Mg	[mg/kg (DM)]	1,826.67	1,857.16	1,570.00	311.14	2,130.00	425.37	2,033.33	471.26	4,583.33	768.02	3,876.67	226.70	2,422.70	799.41	2,244.27	318.98
Al	[mg/kg (DM)]	5,643.33	843.36	6,620.00	1,082.80	6,270.00	373.43	6,276.67	892.49	9,440.00	1,211.45	9,136.67	1,324.14	6,551.97	299.83	7,050.07	448.93
Si	[mg/kg (DM)]	740.00	256.30	1,376.67	257.38	713.33	66.31	643.33	56.96	530.00	166.70	556.67	42.84	693.10	153.67	932.27	104.40
P	[mg/kg (DM)]	223.33	154.47	190.00	70.67	360.00	122.40	430.00	215.90	820.00	22.63	1,056.67	252.36	382.17	41.43	467.07	91.96
K	[mg/kg (DM)]	1,523.33	164.12	1,376.67	254.63	1,383.33	94.90	1,430.00	92.63	2,043.33	213.61	1,963.33	202.53	1,552.93	72.21	1,524.93	36.85
Ca	[mg/kg (DM)]	20,333.33	17,078.01	22,290.00	21,136.07	30,400.00	1,584.25	22,900.00	4,834.23	35,900.00	2,856.05	36,000.00	1,821.15	27,207.67	6,861.29	25,525.80	9,317.40
Ti	[mg/kg (DM)]	450.00	186.29	373.33	101.42	253.33	13.07	206.67	6.53	276.67	17.29	290.00	22.63	337.93	81.42	295.00	37.09
V	[mg/kg (DM)]	5.23	1.83	18.27	23.26	10.77	6.12	8.70	4.71	15.67	3.46	17.00	3.92	9.33	3.71	14.54	9.27
Cr	[mg/kg (DM)]	15.33	4.57	29.00	29.42	22.00	3.92	19.33	3.27	46.33	24.41	37.67	3.46	23.40	7.43	27.43	13.66
Mn	[mg/kg (DM)]	125.00	65.25	253.33	147.25	203.33	55.82	636.67	856.54	883.33	651.47	360.00	29.94	286.82	150.91	414.80	256.38
Fe	[mg/kg (DM)]	27,000.00	34,326.87	10,433.33	2,883.56	19,100.00	4,901.31	19,700.00	3,063.71	42,600.00	1,555.70	44,600.00	4,708.08	26,334.00	12,768.72	21,286.00	2,268.87
Co	[mg/kg (DM)]	4.40	1.02	2.60	0.79	3.30	0.34	2.57	0.17	7.57	1.75	5.57	0.57	4.48	0.23	3.24	0.35
Ni	[mg/kg (DM)]	8.73	1.21	7.43	0.17	14.00	1.13	11.33	1.73	31.33	6.23	26.33	3.97	14.79	1.99	13.00	0.79
Cu	[mg/kg (DM)]	10.50	5.39	9.60	2.40	31.33	14.42	52.67	26.74	74.33	19.93	84.00	35.30	30.10	7.35	41.47	14.59
Zn	[mg/kg (DM)]	83.00*	52.92	73.33	26.23	863.33	1,017.84	266.67	201.26	1,193.33	639.57	1,065.00*	499.80	588.15	323.91	283.00	186.87
As	[mg/kg (DM)]	30.67	40.51	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	-	-	<d.l.	-
Se	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Sr	[mg/kg (DM)]	74.00	55.07	96.33	29.08	95.33	6.43	73.00	6.88	116.67	13.07	103.33	6.53	90.21	23.39	89.47	11.13
Mo	[mg/kg (DM)]	<d.l.	-	<d.l.	-	1.53	0.33	<d.l.	-	1.97	0.47	3.47	0.52	-	-	-	-
Pd	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Ag	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	2.77	3.46	1.07	0.13	-	-	-	-
Cd	[mg/kg (DM)]	<d.l.	-	<d.l.	-	4.00	5.88	<d.l.	-	4.17	0.86	4.43	4.68	-	-	-	-
Sn	[mg/kg (DM)]	3.87	1.44	4.43	4.11	25.33	2.61	27.33	14.24	130.00	49.33	170.00	49.33	34.33	7.45	49.10	12.15
Sb	[mg/kg (DM)]	1.53	1.05	<d.l.	-	1.57	0.46	2.43	2.62	2.53	0.17	3.10	0.41	1.72	0.29	-	-
Te	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Ba	[mg/kg (DM)]	77.33	42.36	106.67	6.53	105.00	14.97	104.33	26.21	840.00	594.82	360.00	79.21	218.61	116.05	161.56	20.08
W	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Hg	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Tl	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Pb	[mg/kg (DM)]	34.00*	1.96	186.00	251.71	136.67	52.27	58.50*	26.46	250.00*	0.00	836.67	191.48	95.03	36.26	276.23	121.92

Notes: <d.l.= amount below detection limit. ar= as received. DM= dry mass. n=3, std. error with Ci of 95%.
*This parameter was determined from 2 measurements (n=2) instead of 3 (n=3).

es U-A and U-E.

Mixed as a single particle size range 90-4.5 mm, the “Inert” fractions are expected to comply with all parameters of the leaching tests: except for NH_4^+ and anionic surfactants.

The contents of NH_4^+ were generally larger in the owc state than in the dry state, which suggests that NH_4^+ is adsorbed to fine-grained particles which in turn are adhered to particles in the owc state and removed in the dry state. No

TABLE 7: Laboratory results of the leaching tests of the “Inert” fractions.

Parameter	Unit	90-30 mm				30-10 mm				10-4.5 mm			
		Owc		Dry		Owc		Dry		Owc		Dry	
		Mean	Std. error	Mean	Std. error	Mean	Std. error	Mean	Std. error	Mean	Std. error	Mean	Std. error
pH	[1]	9.13	0.17	10.30	0.69	8.23	0.69	8.87	0.46	7.27	0.26	7.70	0.00
Electric conductivity	[mS/m]	34.07	4.35	30.17	16.41	40.03	19.65	55.80	38.44	80.00	4.30	60.00	5.63
NH ₄ ⁺	[mg/kg (DM)]	30.67	14.06	20.00	8.98	4.40	1.58	29.33	1.31	16.00	2.99	64.33	9.62
Cl ⁻	[mg/kg (DM)]	113.67	22.92	87.33	23.58	94.67	40.25	43.33	4.71	210.00	11.32	140.00	11.32
SO ₄ ²⁻	[mg/kg (DM)]	980.00	197.30	663.33	102.68	1,090.00	680.09	1,180.00	1,280.07	2,416.67	62.32	1,840.00	238.44
MBAS assay	[mg/kg (DM)]	<d.l.	-	<d.l.	-	1.23	0.36	<d.l.	-	1.07	0.13	1.07	0.13
TOC	[mg/kg (DM)]	52.00	9.09	49.90	20.68	50.23	12.77	58.77	17.60	96.17	2.52	125.67	8.03
KW index	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	0.51	0.02	<d.l.	-
NO ₂ ⁻	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
F ⁻	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Li	[mg/kg (DM)]	0.05	0.02	0.05	0.02	0.05	0.02	0.03	0.01	0.08	0.01	0.04	0.01
Be	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Na	[mg/kg (DM)]	89.67	14.77	64.00	13.34	95.67	28.09	63.33	10.51	183.33	6.53	133.33	6.53
Mg	[mg/kg (DM)]	28.67	12.41	10.57	7.73	42.67	23.26	23.67	15.20	103.00	6.88	66.00	8.84
Al	[mg/kg (DM)]	2.60	2.16	3.77	1.30	3.77	1.14	8.37	7.47	1.63	0.24	1.43	0.07
Si	[mg/kg (DM)]	59.00	18.70	135.00	103.09	25.33	3.64	27.33	11.78	19.00	1.13	23.67	1.73
P	[mg/kg (DM)]	0.64	0.47	0.23	0.10	0.22	0.07	0.56	0.30	0.30	0.04	0.74	0.12
K	[mg/kg (DM)]	100.67	9.22	86.33	10.45	109.33	40.51	113.33	26.13	213.33	6.53	220.00	11.32
Ca	[mg/kg (DM)]	546.67	180.47	466.67	243.32	1,013.33	567.65	713.33	523.16	1,486.67	199.35	996.67	444.99
Ti	[mg/kg (DM)]	0.02	0.01	0.04	0.02	0.01	0.00	0.02	0.01	0.02	0.00	0.02	0.01
V	[mg/kg (DM)]	0.07	0.03	0.76	1.11	0.01	0.00	0.07	0.06	<d.l.	-	<d.l.	-
Cr	[mg/kg (DM)]	<d.l.	-	0.02	0.00	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Mn	[mg/kg (DM)]	0.05	0.03	0.04	0.03	0.09	0.08	0.06	0.05	0.31	0.05	0.57	0.17
Fe	[mg/kg (DM)]	0.64	0.21	0.65	0.54	0.59	0.12	0.88	0.44	1.51	0.57	1.24	0.55
Co	[mg/kg (DM)]	0.02	0.01	0.01	0.00	<d.l.	-	<d.l.	-	0.01	0.00	0.02	0.00
Ni	[mg/kg (DM)]	0.05	0.01	0.03	0.01	0.05	0.02	0.08	0.03	0.10	0.01	0.16	0.02
Cu	[mg/kg (DM)]	0.11	0.01	0.12	0.10	0.10	0.07	0.34	0.28	0.15	0.03	0.24	0.00
Zn	[mg/kg (DM)]	0.06	0.01	0.04	0.02	0.06	0.06	0.06	0.00	0.31	0.12	0.22	0.07
As	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Se	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Sr	[mg/kg (DM)]	1.07	0.13	0.93	0.37	1.51	0.89	1.09	0.89	2.63	0.17	2.07	0.17
Mo	[mg/kg (DM)]	0.13	0.09	0.09	0.05	0.05	0.02	0.06	0.01	0.06	0.01	0.15	0.02
Pd	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Ag	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Cd	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Sn	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	0.02	0.00
Sb	[mg/kg (DM)]	0.01	0.00	0.01	0.00	0.03	0.03	0.03	0.03	0.03	0.01	0.05	0.02
Te	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Ba	[mg/kg (DM)]	0.31	0.03	0.27	0.11	0.48	0.25	0.44	0.22	0.91	0.05	0.88	0.02
W	[mg/kg (DM)]	0.02	0.01	0.03	0.03	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Hg	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Tl	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Pb	[mg/kg (DM)]	0.02	0.00	0.02	0.01	0.02	0.01	0.26	0.43	0.05	0.02	0.03	0.01

Notes: <d.l.= amount below detection limit. ar= as received. DM= dry mass. n=3, std. error with Ci of 95%.

clear trend was identified regarding the anionic surfactants among the particle size ranges and states.

The previous information suggests that, in general, the quality of the “Inert” fractions could be improved if handled as a mixed single particle size range (i.e. 90-4.5 mm). Nonetheless, the mixed single particle size range would very likely still exceed the limit values for NH_4^+ for all quality classes.

3.2.1 Valorization of the Inert fractions as substitute for construction aggregates

Due to the lack of an overarching ordinance in the EU regarding the recycling of construction materials and aggregates, the employment of the “Inert” fractions obtained from landfill-mined waste as a substitute for construction aggregates either falls into a relative grey area of waste legislation in many of the EU countries, or is subjected to ordinances for materials other than landfill-mined waste. For instance, in Austria the “Inert” fractions would need further treatment in order to be valorized as a substitute for construction aggregates according to the RBV. None of the particle size ranges 90-30 mm, 30-10 mm and 10-4.5 mm were strictly suitable for that type of valorization individually, which as previously mentioned would result more problematic than the valorization of these fractions as a mixed single particle size range 90-4.5 mm. Hence, the “Inert” fractions could be valorized as a mixed single particle size range in Austria, provided that they are further processed in a cleaning treatment. This treatment is to be designed in such a way that the amount of anionic surfactants and NH_4^+ are reduced and the limit values set in the RBV can be met. The content of NH_4^+ could be significantly reduced with the implementation of a nitrification process, while the amount of anionic surfactants could be decreased by a washing step. As the problematic parameters in the “Inert” fractions were not exceeded by high amounts, the further treatment of these fractions in order to meet the corresponding limit values seems technically possible: nonetheless, this might render the (E)LFM process economics unfavorable. Furthermore, the valorization of the inert fractions in (E)LFM projects is of critical importance, since they can account for a significant share of the fine fractions; such as in this case study, in which they represent 35.5 wt.% and 37.2 wt.% in the owc and dry states, respectively. Similarly to the combustible fractions, both the recovered inert fractions from the coarse fractions (i.e. the 3D >200 mm and 3D 200-90 mm fractions in the MSG case study) and the fine fractions are likely to be valorized together and, hence, the quality of the overall recovered inert fractions might be substantially improved in this manner, as the inert fractions recovered from the coarse fractions commonly show lower amounts of surface defilements and account for a significant share of the processed material.

It is also relevant to stress, that inert materials obtained through (E)LFM are not precisely included into the scope of the RBV and, therefore, their employment as recycled construction aggregates is not guaranteed even if all specifications have been met. Moreover, additional specifications for this type of valorization, which were not investigated in this study, may apply in the RBV. Therefore, suitable WtM

schemes for the inert fractions recovered from the fine fractions of (E)LFM are to be further developed, while appropriate regulations need to be created at EU level.

4. CONCLUSIONS

The recovered “Combustibles” and “Inert” fractions from the fine fractions <90 mm of the MSG landfill case study corresponded to a material mainly composed of calorific fractions and a material constituted mostly by inorganic components, respectively. From an overarching perspective, the “Combustibles” fractions could be valorized as SRF in (co-)incineration, power and cement plants in the EU, under certain circumstances, since they meet the specifications established in the EN 15359:2011 in both the owc and dry states. These fractions could be valorized mixed in one single particle size range (i.e. 90-4.5 mm) in their original proportions or individually in particle size ranges (i.e. 90-30 mm, 30-10 mm and 10-4.5 mm). However, legislation on waste may vary from country to country in the EU and additional restrictions, as well as stricter limit values, can be applied in a specific member state. For example, in Austria these fractions can be incinerated, but not co-incinerated, according to the limit values for contaminants established in the AVV, as concentrations for As, Cd, Co, Hg and Pb were above the limit values in certain particle size ranges. In general, the quality of these fractions decreased with the decrease in particle size. As a mixed single particle size range only the concentrations of Cd, Hg and Pb exceeded the limit values.

In contrast to conventional (co-)incineration, the plasma gasification process proposed by the NEW-MINE project might offer an appealing WtE valorization route for the combustible fractions obtained from the fine fractions of landfill-mined waste, which in the present case study accounted for 12.5 wt.% and 9.0 wt.% of the total amount of the fine fractions in the owc and dry states, respectively. This valorization route could enable the upcycling of its residues into higher value-added products (e.g. glass-ceramics and inorganic polymers), in addition to the production of high quality energy carriers (e.g. hydrogen or methane): thus contributing to the economic and environmental feasibility of the project.

In Austria the “Inert” fractions would need further treatment in order to be valorized as a substitute for construction aggregates according to the RBV. None of the particle size ranges are strictly suitable for that type of valorization individually, as the contents of hydrocarbons, Cd, Pb, Zn, NH_4^+ and anionic surfactants were above the limit values. As it was the case for the “Combustibles” fractions, the quality of the “Inert” fractions decreased as particle size decreased. The valorization of these fractions as a mixed single particle size range would be less problematic than as individual particle size ranges, since the limit values of less parameters (i.e. hydrocarbons, Pb and NH_4^+) are expected to be exceeded in this way. Hence, the “Inert” fractions could be valorized as a mixed single particle size range in Austria, provided that they are further processed in a cleaning treatment. As the problematic parameters in this fraction were not exceeded by high amounts, the further treat-

ment of these fractions in order to meet the corresponding limit values seems technically possible. Furthermore, the valorization of the inert fractions in (E)LFM projects is of critical importance, since they can account for a significant share of the fine fractions; such as in this case study, in which they represent 35.5 wt.% and 37.2 wt.% in the owc and dry states, respectively. Therefore, suitable WtM valorization schemes for the inert fractions recovered from the fine fractions of (E)LFM are to be further developed and appropriate overarching regulations need to be created at EU level.

It is important to emphasize that both the combustible and inert fractions recovered from the fine fractions are likely to be valorized together with those recovered from the coarse fractions in (E)LFM projects and, therefore, the overall quality of the resulting fractions might be improved in this way, as the fractions recovered from the coarse fractions frequently show better quality and account for a significant share of the processed landfill-mined material.

In general, impurities were associated to the presence of organic and inorganic pollutants and, thus, to a decrease on the valorization potential of both the “Combustibles” and “Inert” fractions. Although the dry state visually presented a lower amount of surface defilements than the owc state, to process these fractions in the dry state did not suffice to comply with the corresponding Austrian limit values. Therefore, cleaning methods would be needed to remove the contaminants from the “Combustibles” and “Inert” fractions in Austria. However, it seems unlikely that those methods will be economically feasible, as prices of primary raw materials and regulations remain to be daunting obstacles for (E)LFM. The increasing market prices of primary raw materials, the development of a holistic legal framework for secondary raw materials and the raising public awareness will set the conditions to justify further material and energy recovery from the fine fractions from (E)LFM, as well as the employment of innovative waste processing and cleaning technologies.

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