Grain-size specific characterisation and resource potentials of municipal solid waste incineration (MSWI) bottom ash: A German case study

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Supplementary Information

S.1. German limit values for utilisation of MSWI bottom ash

In Germany there is a draft regulation on the use of secondary building materials (SBM). In this draft it is distinguished between three qualities of the MSWI BA, called HMVA-1, HMVA-2, and HMVA-3. HMVA-1 represent the best quality for MSWI BA utilisation with strictest limit values [1].

LAGA M 20 is a recommendation with requirements for the utilisation of mineral residues and eastes [2]. According to LAGA M 20 MSWI BA may be utilised in technical constructions with defined safety measures, so called construction class Z 2. Examples of such technical constructions are:

- Road construction
  - base layer under a impermeable top layer (concrete)
  - bound base layer under a less permeable top layer (paving)
- Anti-noise barrier.

TL Gestein-StB 04 presents requirements on aggregates in road construction. In this recommendation the utilisation of MSWI BA as aggregate in road construction is characterised by the leaching contents.

Table S1 summarises the limit values of the mentioned regulations and recommendations.

Table S1: Limit values for recycling of mineral residues and wastes in Germany according to different regulations and recommendations

Parameter	Unit	Draft SBM HMVA-1	LAGA M 20 Z 2	TL Gestein-StB 04
Leachate method	-	DIN 19529	DIN EN 12457-4	DIN EN 12457-4
pH-value	-	7 - 13	7 - 13	7 - 13
Conductivity	µS/cm	2.000	6000	2.000
Chloride	mg/l	160	250	50
Sulphate	mg/l	820	600	200
Antimony	µg/l	10	-	-
Chromium total	µg/l	150	200	50
Copper	µg/l	110	300	300
Molybdenum	µg/l	55	-	-
Vanadium	µg/l	55	-	-
Lead	µg/l	-	50	50
Cadmium	µg/l	-	5	5
Nickel	µg/l	-	40	40
Mercury	µg/l	-	1	1
Zinc	µg/l	-	300	300

S.2. Samples overview

The required sample mass was determined by estimating the material heterogeneity and by a maximum of acceptable sampling error. The material heterogeneity was estimated by means of the Heterogeneity Invariant HI_L (cf. Equation (1)) [3]. All formulas and definitions can be seen in Gy (1992).

$$HI_L = \frac{1}{m_L} \cdot \sum_i \left(\frac{(c_i - c_L) \cdot m_i}{c_L}\right)^2 \qquad (1)$$

HI_L Heterogeneity Invariant

m_L mass of the lot L

m_i mass of the particle i

c_L concentration of the analyte in the lot L

c_i concentration of the analyte in the particle i

The sampling aim was to determine the content of non-ferrous metals (NFe) with a maximum relative standard error of 10%. The non-ferrous metals were chosen as an analyte due to their low mass in the MSWI BA. It was assumed that the concentration of the NFe metals in the lot is 1.7% and the mass of the lot is 1000 kg.

Following was assumed for the mass and concentration in different grain sizes:

Table S2: Assumed values for calculating the HI_L

Grain size	m_i [kg]	c_i
0-2 mm	200.00	1.0%
2-4 mm	100.00	2.3%
4-8 mm	140.00	2.3%
8-16 mm	210.00	2.2%
16-32 mm	100.00	2.0%
> 31.5 mm	250.00	1.2%

These assumptions are based on previous unpublished investigations of the MSWI BA from the WtE plant in Kassel. With this data the HI_L was calcalated as 19.2 kg. Furthermore, the required sample mass was calculated according to Equation (2).

$$s_{sampling} = \sqrt{\frac{HI_L}{m_{sample}}} \qquad (2)$$

The calculated required sample mass is 1,917 kg.

In total 40 increments with a total mass of 1,724 kg were taken. There is a deviation from the calculated required sample mass due to the operational process of the plant. The mass variation of the increment is shown in Figure S1.

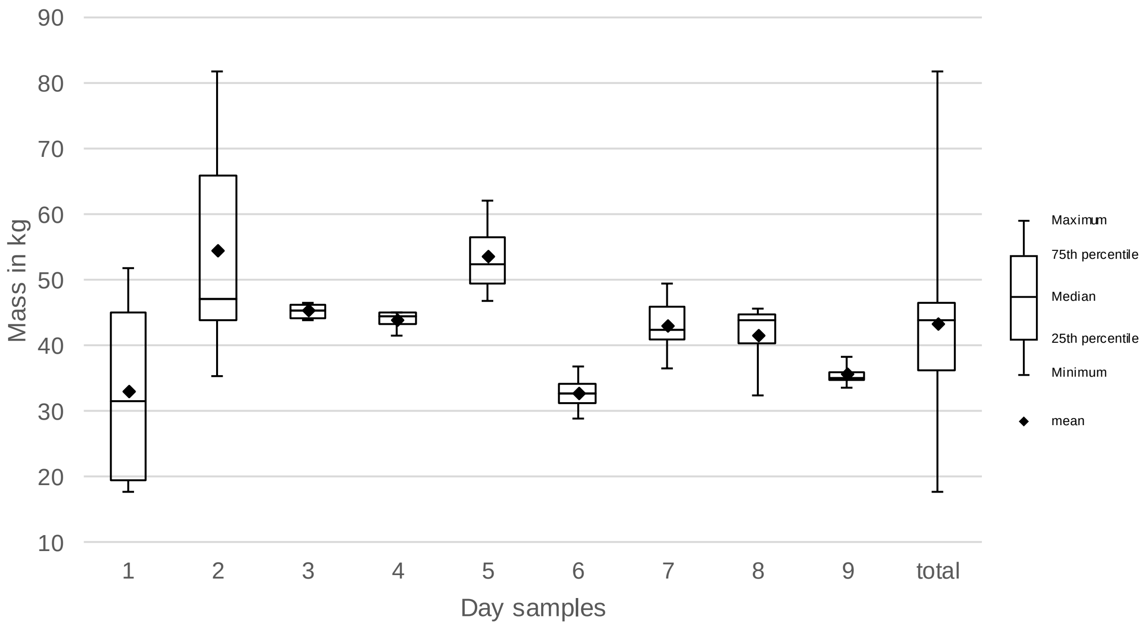

Figure S1: Distribution of the mass of the increments in the nine daily samples and in the whole sample

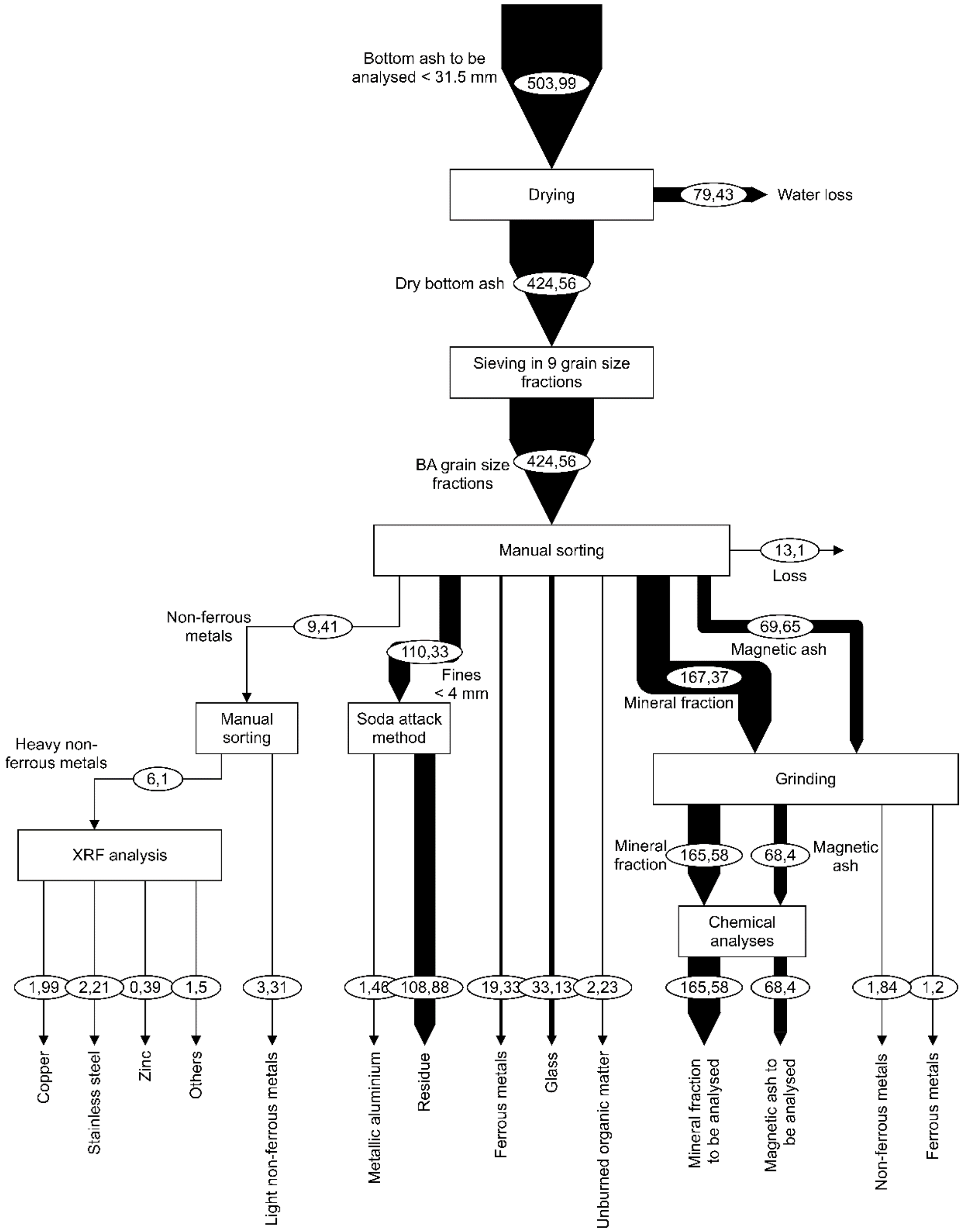

Figure S2: Mass flows in [kg] determined by the analysis of the raw MSWI BA smaller than 31.5 mm

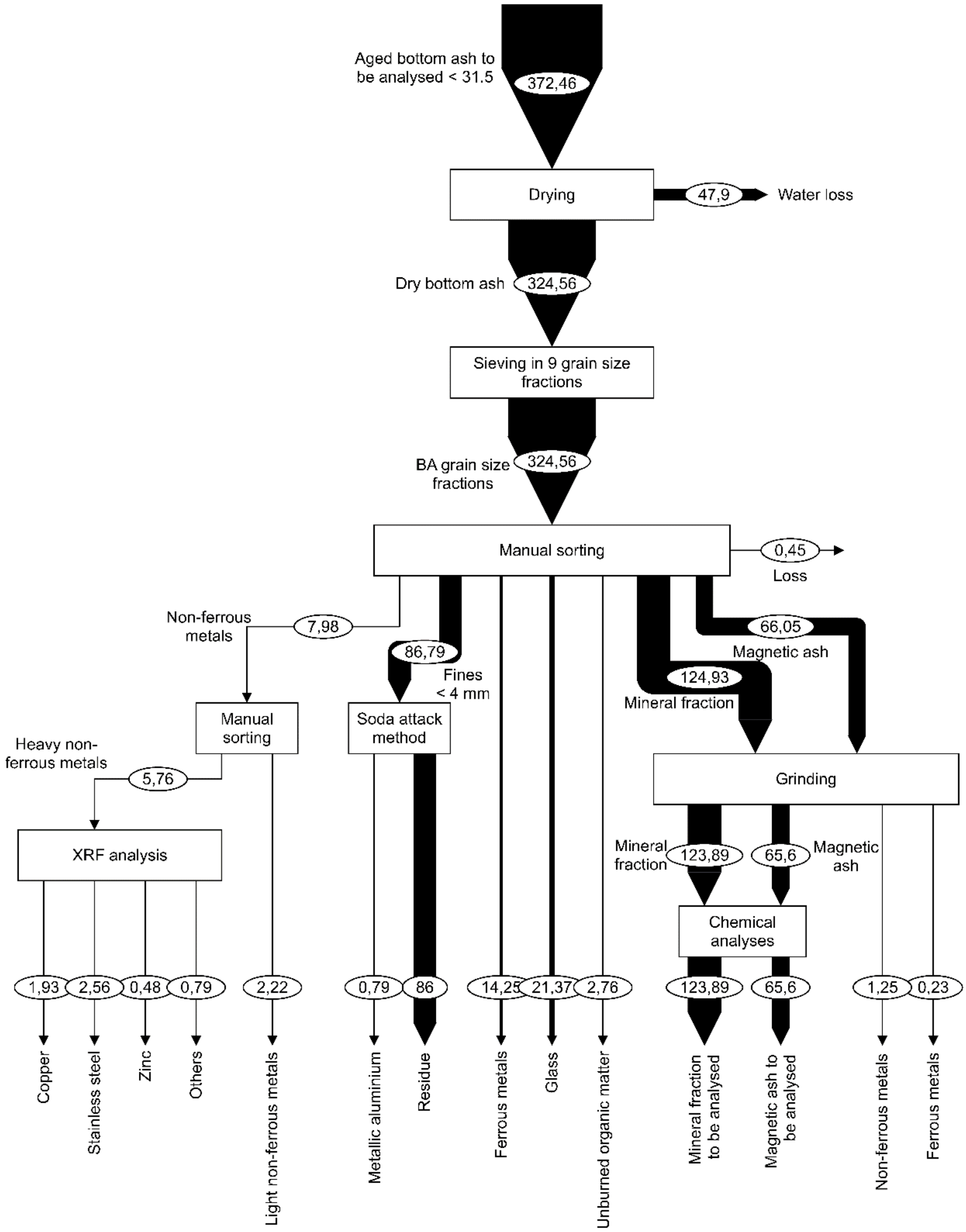

Figure S3: Mass flows in [kg] determined by the analysis of the aged MSWI BA smaller than 31.5 mm

S.3 Determination of the metallic aluminium content in the fine fraction

The metallic aluminium reacts with sodium hydroxide solution according to Equation (3). The content of the metallic aluminium was calculated by means of the volume of hydrogen gas generated (Eq. (4)).

$$2Al + 2OH^- + 2H_2O \rightarrow 2AlO_2^- + 3H_2 \tag{3}$$

$$Al\,[\%] = \frac{p \cdot \Delta V \cdot M_{Al} \cdot n_{Al}}{R \cdot T \cdot M_{H_2} \cdot n_{H_2} \cdot m_{BA}} \tag{4}$$

p	atmospheric pressure [bar]
ΔV	volume of the generated hydrogen gas [l]
R	gas constant (0.0416 bar·l·g^{-1}·K^{-1})
T	temperature [K]
M_{Al}	molar mass of aluminium [g/mol]
n_{Al}	stoichiometric amount of aluminium [mol]
M_{H2}	molar mass of hydrogen [g/mol]
n_{H2}	stoichiometric amount of hydrogen [mol]
m_{BA}	mass if the BA sample [g]

For the determination of the metallic aluminium appr. 10 g of BA were put in contact with sodium hydroxide solution with a concentration of 30 wt.%. BA from the grain size fractions 2-4 mm, 1-2 mm, 0.063-1 mm, and < 0.063 mm was analysed. The analysis was carried out in triplicate.

S.4 Designing a mixture of the mineral fraction according to the Fuller curve

A mixture of the mineral fraction was designed after metal recovery. The assumed recovery rates for the metals to assess utilisable resource potentials of metals and the processed BA are shown in Table S3.

Table S3: Assumed recovery rate of the metals for assessment of the utilisation potential of the mineral fraction after metal recovery. Sources: [4,5]

Grain size	Fe	NFe
> 32 mm	90%	70%
8-32 mm	85%	62%
2-8 mm	80%	50%
< 2 mm	-	-
mean	85%	61%

The Fuller curve is a grading curve providing an ideal particle size distribution for aggregates resulting in best properties of concrete [6]. The Fuller curve depends on the aggregate shape. In this study, it was assumed that the aggregates have spherical shapes. An example for a particle size distribution after Fuller with spherical aggregate is shown in Table S4. The calculation can be seen in Wriggers and Moftah (2006) [6].

Table S4: Cumulative particle size distribution after Fuller for aggregate with spherical shape, where P(d) is the percentage passing a sieve with mesh size diameter d

d [mm]	0.063	0.125	0.25	0.5	1	2	4	8	16	20	25	31.5
P(d) [%]	4.5	6.3	8.9	12.6	17.8	25.2	35.6	50.4	71.3	79.7	89.1	100.0

The particle size distribution of the residual mineral fraction after metal recovery was compared with the particle size distribution of the Fuller curve (Table S4). For example, the coarse fraction above 31.5 mm was not usable as aggregate in concrete. In this way, a mixture of aggregate was designed that is comparable to the Fuller curve. The leaching concentrations, residual metal contents and glass content of this mixture were determined.

S.5 Results

S.5.1 Material composition

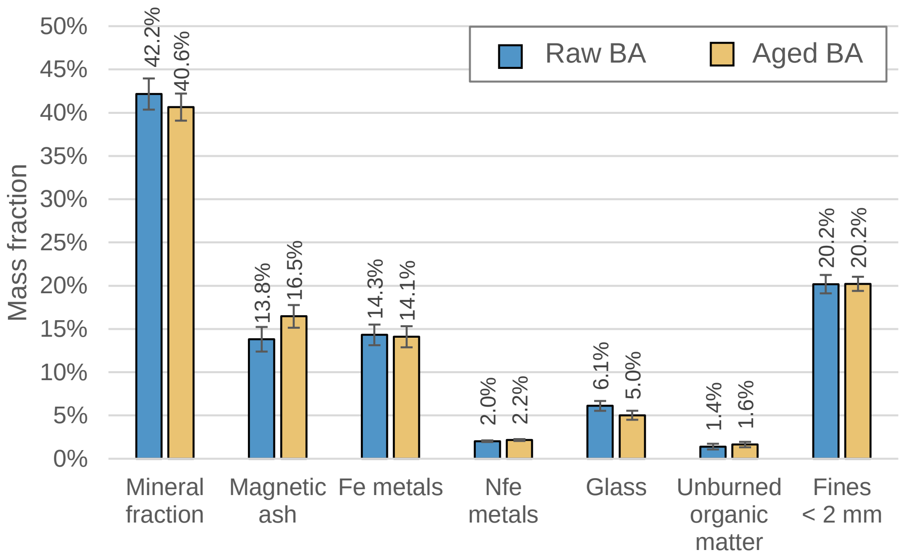

Figure S4: Total material composition of the raw and aged MSWI BA; error bars show the standard error of the nine daily samples

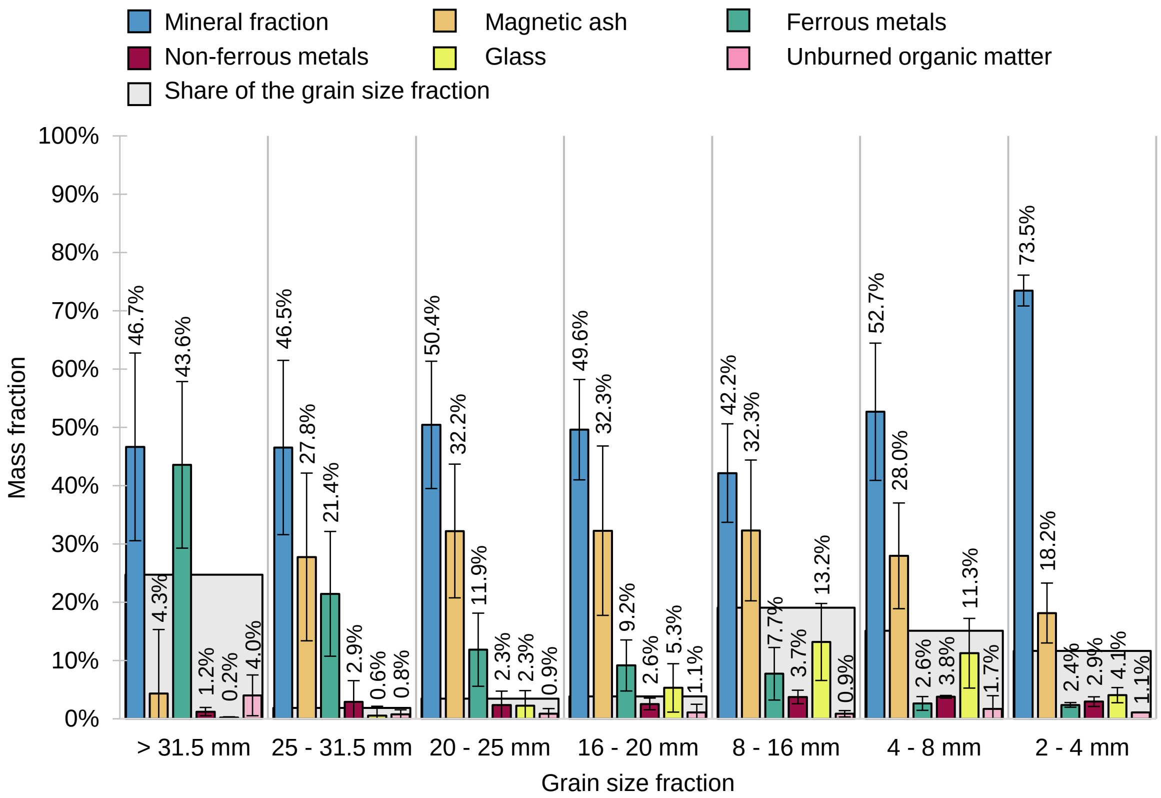

Figure S5: Composition of the aged MSWI BA as a function of the particle size; error bars show the standard deviation of the nine daily samples

Table S5: Statistical measures of the material contents of the raw and aged MSWI BA > 2 mm considering the nine daily samples. Abbreviations: SD: standard deviation; RSD: relative standard deviation; SE: standard error; RSE: relative standard error

Fraction	Raw BA					Aged BA					Relative difference
	Mean	SD	RSD	SE	RSE	Mean	SD	RSD	SE	RSE	
Mineral fraction	42.2%	5.4%	12.8%	1.8%	4.3%	40.6%	4.7%	11.6%	1.6%	3.9%	3.6%
Magnetic ash	13.8%	4.3%	30.9%	1.4%	10.3%	16.5%	3.9%	23.9%	1.3%	8.0%	19.2%
Fe metals	14.3%	3.6%	25.0%	1.2%	8.3%	14.1%	3.7%	26.0%	1.2%	8.7%	1.5%
NFe metals	2.0%	0.3%	14.1%	0.1%	4.7%	2.2%	0.3%	14.9%	0.1%	5.0%	6.8%
Glass	6.1%	1.7%	28.0%	0.6%	9.3%	5.0%	1.6%	31.2%	0.5%	10.4%	17.7%
Unburned OM	1.4%	1.0%	70.6%	0.3%	23.5%	1.6%	0.9%	57.3%	0.3%	19.1%	16.7%
Fines < 2 mm	20.2%	3.2%	15.8%	1.1%	5.3%	20.2%	2.5%	12.1%	0.8%	4.0%	0.2%

S.5.2 Composition of the non-ferrous metals

The composition of the non-ferrous metals over 4 mm determined by the manual sorting is shown in Figure S6. The most common metal in the coarse fraction over 31.5 mm is steel. In all other grain size fraction Al has the highest content which is between 36.9% and 66.8%. The aluminium content in the NFe-metal fraction is lower compared to previous studies [4,7,8].

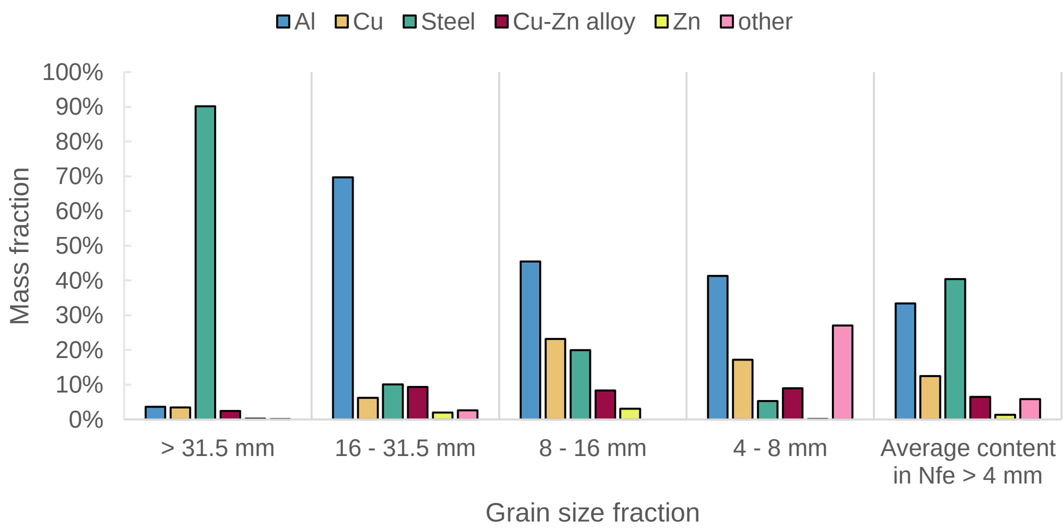

Figure S6: Composition of the non-ferrous metals in the grain size fractions over 4 mm in the raw MSWI bottom ash

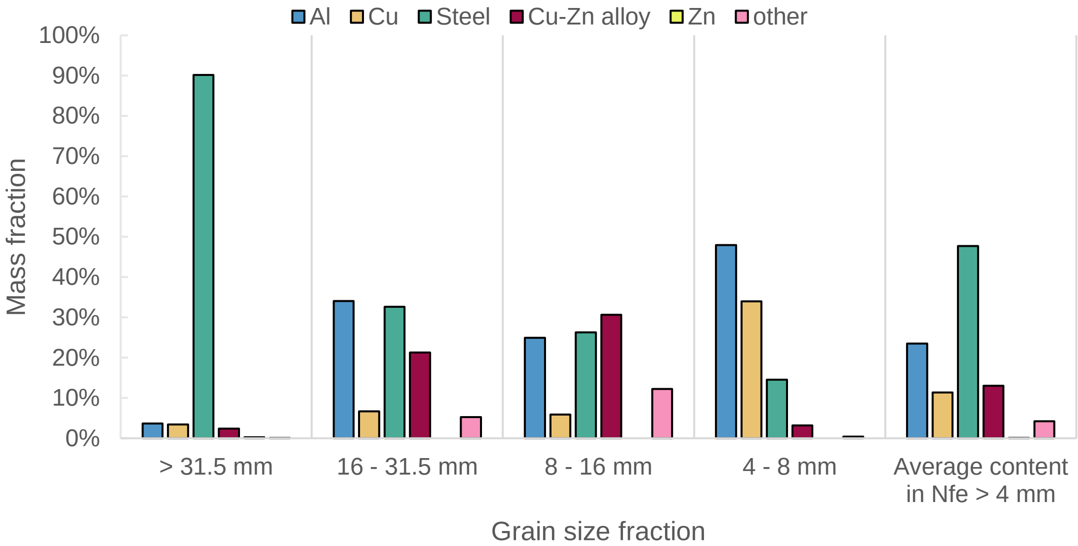

Figure S7: Composition of the non-ferrous metals in the grain size fractions over 4 mm in the aged MSWI BA

S.5.3 Total contents

Table S6: Mass fraction of all elements analysed in the non-ferrous metals fraction above 4 mm of the raw BA in [mg/kg dry matter]; LOD: limit of determination; ND: not determined

Element	*Grain size*							
	> 31.5 mm		16 - 31.5 mm		8 - 16 mm		4 - 8 mm	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Ag	< LOD	-	1.1	0.1	0.4	0.1	402.8	41.5
Al	30,102	119	494,310	1,125	409,960	1,725	366,669	669
As	ND	-	ND	-	ND	-	ND	-
Au	< LOD	-	14.0	0.8	< LOD	-	< LOD	-
Bi	36.0	0.5	176.6	7.6	4.2	0.3	1,194.8	136.8
Ca	ND	-	ND	-	ND	-	ND	-
Cd	< LOD	-	6.1	0.2	4.2	0.4	5.8	0.3
Co	695.6	5.0	252.7	5.4	72.0	6.6	42.0	2.9
Cr	17,420	127	12,812	277	6,421	503	2,743	192
Cu	93,603	655	122,753	1,740	283,177	3,573	214,677	1,170
Fe	784,712	534	106,567	1,126	195,397	2,284	54,500	732
Hf	< LOD	-	11,958.8	731.7	< LOD	-	662.6	67.3
K	ND	-	ND	-	ND	-	ND	-
Mg	1.7	0.0	17,370.5	139.5	58.9	0.7	673.5	56.5
Mn	1,426.7	12.8	4,242.1	76.7	1,246.5	74.9	400.2	23.7
Mo	649.0	13.4	585.0	15.5	110.6	20.4	29.2	1.9
Nb	17.5	0.2	17.5	0.3	7.0	0.3	7.4	0.3
Ni	19,118	126	11,805	209	4,208	275	4,393	189
P	56.0	0.5	160.5	3.1	209.5	13.3	78.2	2.7
Pb	1,107.9	11.3	528.9	6.1	601.1	37.3	3,734.0	403.3
Pd	< LOD	-	3.0	0.2	1.8	0.1	2.6	0.2
Rb	ND	-	ND	-	ND	-	ND	-
S	3,242	27	6,718	81	5,627	223	4,070	86
Sb	40.4	0.4	125.8	16.5	25.9	1.3	456.9	62.7
Se	< LOD	-	16.6	1.0	< LOD	-	78.1	12.1
Si	8,202	78	126,272	983	29,408	526	19,190	491
Sn	1,964.9	23.9	580.7	11.3	317.3	24.4	389.1	23.3
Ta	312.2	8.2	< LOD	-	< LOD	-	846.1	97.9
Ti	1,956.0	58.1	9,392.2	108.8	570.4	21.7	910.0	27.5
V	107.0	0.7	545.0	4.2	70.0	2.8	56.9	2.1
W	1,748.8	41.3	3,289.7	138.8	8.7	1.1	335.7	22.1
Zn	24,208	271	58,663	996	49,164	1,894	30,177	776
Zr	100.1	0.0	127.3	1.4	58.9	3.2	22.7	1.5

Table S7: Mass fraction of all elements analysed in the ferrous metals fraction above 4 mm of the raw BA in [mg/kg dry matter]; LOD: limit of determination; ND: not determined

	Grain size							
Element	> 31.5 mm		16 - 31.5 mm		8 - 16 mm		4 - 8 mm	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Ag	<LOD	-	<LOD		<LOD	-	<LOD	-
Al	1,143	26	4,800	157	25,389	1,386	32,139	1,253
As	ND	-	ND	-	ND	-	ND	-
Au	<LOD	-	<LOD	-	<LOD	-	<LOD	-
Bi	108.2	0.3	6.2	0.2	<LOD	-	4.8	0.2
Ca	ND	-	ND	-	ND	-	ND	-
Cd	<LOD	-	<LOD	-	1.9	0.5	<LOD	-
Co	6,698.9	28.8	2,971.8	74.4	1,672.7	109.2	2,247.7	209.3
Cr	4,887	70	14,678	1,045	9,068	1,755	5,830	2,061
Cu	4,349	17	12,400	669	2,530	61	34,885	2,826
Fe	915,476	448	539,411	18,647	781,287	6,602	744,236	9,237
Hf	ND	-	ND	-	ND	-	ND	-
K	ND	-	ND	-	ND	-	ND	-
Mg	ND	-	ND	-	ND	-	ND	-
Mn	3,205.4	14.8	2,114.3	88.5	6,841.4	446.8	3,609.2	371.4
Mo	313.6	1.3	371.4	20.6	210.8	13.8	218.8	22.5
Nb	195.6	0.8	10.4	0.4	23.2	1.5	28.1	2.5
Ni	8,884	150	8,402	973	84,032	6,992	5,616	1,592
P	56.1	0.2	362.6	15.6	684.3	44.7	983.9	101.3
Pb	614.3	6.6	<LOD	-	199.7	9.9	289.4	19.8
Pd	<LOD	-	<LOD	-	<LOD	-	<LOD	-
Rb	ND	-	ND	-	ND	-	ND	-
S	11,709	48	6,918	269	16,380	1,070	28,865	2,971
Sb	<LOD	-	<LOD	-	27.8	1.1	287.8	22.9
Se	<LOD	-	<LOD	-	<LOD		<LOD	
Si	10,102	43	14,849	576	65,163	4,256	115,717	11,909
Sn	0.4	0.0	371.2	11.2	21.2	0.8	44.1	3.5
Ta	ND	-	ND	-	ND	-	ND	-
Ti	3,758.3	17.3	1,110.4	44.8	2,395.8	156.5	6,207.3	638.8
V	110.5	0.3	216.0	9.6	319.6	20.9	460.6	47.4
W	2,618.7	6.3	39.0	0.9	<LOD	-	390.2	17.7
Zn	25,161	261	2,390	172	3,707	64	17,782	2,240
Zr	412.9	1.9	10.3	0.2	31.2	0.8	162.9	15.9

Table S8: Mass fraction of all elements analysed in mineral fraction above 4 mm of the raw BA in [mg/kg dry matter]; LOD: limit of determination; ND: not determined

Element	*Grain size*							
	> 31.5 mm		16 - 31.5 mm		8 - 16 mm		4 - 8 mm	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Ag	11.6	2.5	10.7	5.0	12.7	1.1	7.9	4.4
Al	20,631	577	21,695	3,776	19,596	592	18,821	1,098
As	1.9	3.1	14.2	11.8	4.0	3.7	30.1	25.8
Au	< LOD	-	< LOD	-	< LOD	-	< LOD	-
Ba	815.7	42.8	919.5	130.5	1,608.0	228.6	1,532.0	169.2
Bi	< LOD	-	< LOD	-	< LOD	-	< LOD	-
Ca	174,029	17,178	127,593	6,118	126,984	5,265	143,256	8,531
Cd	1.3	0.1	1.4	0.8	2.4	0.6	5.9	2.7
Cl	10,243.1	3,006.9	10,531.6	413.4	10,339.7	396.0	8,333.8	708.9
Co	< LOD	-	< LOD	-	< LOD	-	< LOD	-
Cr	242	31	195	64	234	5	224	13
Cu	1,796	1,723	2,335	290	4,427	3,393	2,507	687
Fe	34,051	1,950	39,193	5,172	51,064	826	57,354	2,388
Hf	ND	-	ND	-	ND	-	ND	-
K	10,597	423	12,025	499	9,381	188	8,929	446
Mg	24,990.8	22,066.9	22,357.0	14,340.0	12,796.7	9,765.9	4,066.5	5,245.1
Mn	691.9	403.9	808.7	94.3	827.7	90.4	721.5	347.5
Mo	103.4	6.3	46.9	3.3	49.6	5.9	59.4	30.1
Nb	18.1	1.8	21.0	1.3	20.0	3.7	16.2	2.5
Ni	134	15	116	22	184	6	269	105
P	396.0	95.9	1,382.8	103.4	1,161.7	154.6	1,297.5	168.6
Pb	258	142	182	36	454	89	582	189
Pd	7.3	6.8	5.5	4.3	3.8	2.9	2.2	2.7
Rb	47	5	61	4	42	5	28	6
S	67,513	871	13,126	622	19,082	1,030	25,591	7,452
Sb	50.6	9.0	84.6	12.3	108.8	16.0	85.4	9.8
Se	< LOD	-	< LOD	-	< LOD	-	< LOD	-
Si	167,790	3,222	214,927	6,871	191,235	1,673	194,148	5,525
Sn	64.2	8.1	75.5	11.1	107.3	12.2	100.3	22.3
Ta	ND	-	ND	-	ND	-	ND	-
Ti	6,126.1	928.9	5,688.0	529.6	6,232.2	200.1	7,352.8	1,084.3
V	57.0	49.7	97.8	41.5	42.5	36.8	39.0	41.1
W	< LOD	-	< LOD	-	< LOD	-	35.9	62.3
Zn	1,524	86	1,976	398	2,158	288	3,788	419
Zr	344	17	730	120	668	270	387	174

Table S9: Mass fraction of all elements analysed in the mineral fraction below 4 mm of the raw BA in [mg/kg dry matter]; LOD: limit of determination; ND: not determined

Element	*Grain size*							
	2 - 4 mm		1 - 2 mm		0.063 - 1 mm		< 0.063 mm	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Ag	23	6	16	5	8	7	16	3
Al	19,767	208	32,400	4,122	25,433	2,650	15,500	1,400
As	13	23	37	12	< LOD	-	< LOD	-
Au	< LOD	-	< LOD	-	< LOD	-	< LOD	-
Ba	1,184	202	1,322	751	1,294	175	1,089	79
Bi	< LOD	-	< LOD	-	< LOD	-	< LOD	-
Ca	188,359	1,078	168,646	24,023	220,591	4,980	284,585	2,615
Cd	5.1	2.9	15.3	16.7	32.2	8.4	30.1	15.7
Cl	13,278.2	231.2	11,147.1	343.4	11,213.1	428.2	13,617.6	597.0
Co	< LOD	-	< LOD	-	< LOD	-	< LOD	-
Cr	244	27	262	32	326	48	227	6
Cu	2,783	321	7,847	3,920	3,167	551	1,317	59
Fe	63,267	4,697	71,967	4,315	50,333	3,690	19,000	964
Hf	ND	-	ND	-	ND	-	ND	-
K	9,104	534	7,344	795	6,265	181	5,395	182
Mg	10,689	18,513	< LOD	-	< LOD	-	< LOD	-
Mn	1,237	98	1,228	187	795	795	539	71
Mo	51	9	191	140	33	6	50	5
Nb	19.4	0.9	14.5	12.7	16.1	3.8	9.2	8.0
Ni	221	33	223	39	295	34	183	15
P	922	799	733	147	506	464	726	42
Pb	394	45	2,040	1,170	887	332	629	33
Pd	0.0	0.0	6.5	5.7	0.0	0.0	0.0	0.0
Rb	32	2	34	9	28	4	19	19
S	49,075	1,320	34,439	5,412	46,359	46,359	59,360	59,360
Sb	90	22	70	26	104	7	152	19
Se	< LOD	-	< LOD	-	< LOD	-	< LOD	-
Si	118,099	2,646	76,360	15,329	68,672	3,861	48,842	1,564
Sn	99	7	75	27	230	109	153	7
Ta	ND	-	ND	-	ND	-	ND	-
Ti	10,742	75	10,864	1,940	8,376	448	10,506	527
V	< LOD	-	< LOD	-	< LOD	-	< LOD	-
W	< LOD	-	< LOD	-	< LOD	-	< LOD	-
Zn	4,930	596	6,237	1,615	3,350	246	3,460	219
Zr	372	206	128	18	275	206	125	125

Table S10: Mass fraction of all elements analysed in the non-ferrous metals fraction of the aged BA in [mg/kg dry matter]; LOD: limit of determination; ND: not determined

	Grain size							
Element	> 31.5 mm		16 - 31.5 mm		8 - 16 mm		4 - 8 mm	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Ag	< LOD		< LOD		< LOD		1,436.7	557.1
Al	30,102	119	347,509	2,062	233,547	2,307	438,744	5,043
As	ND		ND		ND		ND	
Au	< LOD		< LOD		< LOD		< LOD	
Bi	36.0	0.5	8.7	0.5	2.9	0.3	3.9	1.2
Ca	ND		ND		ND		ND	
Cd	< LOD		< LOD		< LOD		2.6	0.0
Co	696	5	516.8	13.5	61.7	10.1	< LOD	
Cr	17,420	127	17,721	580	2,941	407	250	76
Cu	93,603	655	173,693	3,117	235,663	3,884	358,681	4,657
Fe	784,712	534	271,457	3,097	287,865	2,712	131,347	927
Hf	< LOD		< LOD		6.0	1.4	< LOD	
K	ND		ND		ND		ND	
Mg	1.7	0.0	4,550.0	267.4	5,683.7	478.8	859.3	523.0
Mn	1,426.7	12.8	2,341.6	61.9	1,418.1	54.8	251.6	38.9
Mo	649.0	13.4	878.2	37.4	55.7	4.1	28.6	7.9
Nb	17.5	0.2	18.5	0.4	8.7	0.3	10.0	1.7
Ni	19,118	126	15,901	556	25,413	1,321	442	136
P	56.0	0.5	204.6	6.1	289.6	4.9	74.4	10.8
Pb	1,108	11	3,223	123	7,075	332	629	109
Pd	< LOD		< LOD		< LOD		< LOD	
Rb	ND		ND		ND		ND	
S	3,242	27	16,176	385	14,578	288	4,476	628
Sb	40	0	8	0	27	8	27	6
Se	< LOD		< LOD		< LOD		< LOD	
Si	8,202	78	56,619	1,075	83,401	1,922	19,004	2,986
Sn	1,964.9	23.9	575.8	27.1	762.7	12.2	268.3	44.3
Ta	312.2	8.2	< LOD		< LOD		< LOD	
Ti	1,956.0	58.1	6,727.9	444.4	4,907.4	109.0	1,739.0	317.3
V	107.0	0.7	2,341.6	61.9	1,418.1	54.8	251.6	38.9
W	1,748.8	41.3	3,710.6	218.7	1,393.4	50.8	474.2	93.2
Zn	24,208	271	76,334	2,283	92,588	1,583	31,011	2,618
Zr	100.1	1.5	507.6	25.2	67.6	3.2	53.9	15.3

Table S11: Mass fraction of all elements analysed in the ferrous metals fraction of the aged BA in [mg/kg dry matter]; LOD: limit of determination; ND: not determined

	Grain size							
Element	> 31.5 mm		16 - 31.5 mm		8 - 16 mm		4 - 8 mm	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Ag	<LOD	-	<LOD	-	<LOD	-	<LOD	-
Al	1,143	1	16,538	976	13,390	464	9,850	1,461
As	ND	-	ND	-	ND	-	ND	-
Au	<LOD	-	<LOD	-	<LOD	-	<LOD	-
Bi	108.2	0.3	<LOD	-	<LOD		49.5	5.2
Ca	ND	-	ND	-	ND	-	ND	-
Cd	0.0	0.0	230.8	11.7	174.5	8.6	2.6	1.4
Co	6,698.9	28.8	3,298.5	98.3	6,892.1	212.2	3,613.3	102.8
Cr	4,887	23	20,403	853	1,698	34	8,419	3,399
Cu	4,349	20	6,786	1,601	2,636	57	17,550	1,184
Fe	915,476	4,226	829,302	8,286	5,265	2,636	900,850	7,123
Hf	ND	-	ND	-	ND	-	ND	-
K	ND	-	ND	-	ND	-	ND	-
Mg	ND	-	ND	-	ND	-	ND	-
Mn	3,205.4	14.8	6,873.8	246.4	16,626.6	694.7	3,805.3	208.0
Mo	313.6	1.3	261.4	10.6	117.4	5.8	763.0	55.7
Nb	195.6	0.8	40.9	1.8	14.4	0.8	4.3	1.5
Ni	8,884	11	8,764	1,465	65,102	3,891	8,889	2,121
P	56.1	0.2	449.6	20.0	320.5	11.8	291.7	41.5
Pb	614	1	377	196	303	21	<LOD	-
Pd	<LOD	-	<LOD	-	8.1	0.6	<LOD	-
Rb	ND	-	ND	-	ND	-	ND	-
S	11,709	48	16,164	682	13,807	534	9,798	1,104
Sb	0.0	0.0	58.9	28.6	50.4	4.6	<LOD	-
Se	<LOD	-	<LOD	-	<LOD	-	<LOD	-
Si	10,102	43	43,243	2,629	34,171	1,472	28,039	2,953
Sn	145.8	0.4	56.0	10.8	102.0	18.2	246.2	25.0
Ta	ND	-	ND	-	ND	-	ND	-
Ti	3,758.3	17.3	3,431.6	134.3	3,164.1	107.4	1,962.8	199.7
V	110.5	0.3	335.6	11.6	296.2	7.7	267.0	19.0
W	2,618.7	6.3	<LOD	-	<LOD	-	9.4	5.2
Zn	25,161	116	7,513	152	5,030	115	5,507	2,672
Zr	413	2	189	16	166	8	34	5

Table S12: Mass fraction of all elements analysed in the mineral fraction above 4 mm of the aged BA in [mg/kg dry matter]; LOD: limit of determination; ND: not determined

Element	*Grain size*							
	> 31.5 mm		16 - 31.5 mm		8 - 16 mm		4 - 8 mm	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Ag	0.1	0.0	0.8	0.0	3.0	0.0	4.5	3.5
Al	28,833	4,567	29,156	2,601	22,242	2,312	19,752	7,163
As	< LOD	-	< LOD	-	< LOD	-	< LOD	-
Au	< LOD	-	< LOD	-	< LOD	-	< LOD	-
Ba	1,614.5	265.0	1,441.7	117.5	1,616.0	29.3	1,159.2	69.5
Bi	21.5	0.0	< LOD	-	< LOD	-	< LOD	-
Ca	104,950	1,113	156,069	35,344	153,253	1,530	166,001	1,501
Cd	23.5	18.1	2.8	0.3	2.8	0.3	2.4	0.9
Cl	5,803.9	1,314.2	4,976.4	132.9	9,929.2	247.2	8,770.4	65.8
Co	866.8	69.8	1,051.5	45.2	1,117.3	33.3	1,121.7	50.7
Cr	226	45	331	46	243	31	173	63
Cu	1,437	185	1,471	429	1,131	433	1,764	1,090
Fe	71,647	16,180	54,261	3,222	35,768	4,021	33,576	4,679
Hf	ND	-	ND	-	ND	-	ND	-
K	10,405	151	10,305	2,113	8,412	67	9,635	281
Mg	20,836.6	1,458.8	22,622.9	8,930.4	25,099.0	8,756.9	3,705.2	6,798.3
Mn	517.0	71.4	860.8	90.3	649.8	12.1	658.1	30.9
Mo	40.5	5.3	79.0	8.2	64.9	3.5	45.9	1.2
Nb	27.9	5.3	20.1	6.8	23.0	5.9	20.4	0.0
Ni	151	35	236	50	152	20	111	34
P	825.3	495.1	1,071.5	455.6	770.8	35.6	1,087.1	74.3
Pb	346	165	712	201	276	281	311	132
Pd	< LOD	-	< LOD	-	< LOD	-	< LOD	-
Rb	< LOD	-	< LOD	-	< LOD	-	< LOD	-
S	8,129	2,664	9,053	278	23,706	970	23,913	220
Sb	64.4	10.6	78.9	15.9	85.9	8.8	83.4	10.0
Se	< LOD	-	< LOD	-	< LOD	-	< LOD	-
Si	205,602	2,312	190,077	27,570	167,393	4,432	181,893	5,938
Sn	114.1	18.3	154.2	21.7	119.0	12.1	109.1	10.0
Ta	ND	-	ND	-	ND	-	ND	-
Ti	9,047.8	679.3	7,282.9	755.0	8,359.2	88.4	9,198.3	152.7
V	137.2	15.8	104.7	33.5	112.6	28.6	83.8	45.3
W	< LOD	-	58.8	34.0	< LOD	-	< LOD	-
Zn	2,209	1,401	2,344	367	4,119	1,259	3,804	1,647
Zr	448	56	829	333	222	6	282	106

Table S13: Mass fraction of all elements analysed in the mineral fraction below 4 mm of the aged BA in [mg/kg dry matter]; LOD: limit of determination; ND: not determined

	Grain size							
Element	2 - 4 mm		1 - 2 mm		0.063 - 1 mm		< 0.063 mm	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Ag	< LOD	-	< LOD	-	7	12	17	15
Al	25,633	4,594	24,633	3,842	19,867	950	20,467	1,617
As	< LOD	-	< LOD	-	< LOD	-	< LOD	-
Au	< LOD	-	< LOD	-	< LOD	-	< LOD	-
Ba	970	78	393	210	1,323	250	1,183	437
Bi	< LOD	-	< LOD	-	< LOD	-	< LOD	-
Ca	85,187	3,555	162,777	8,394	174,847	1,219	189,780	4,265
Cd	4.0	1.0	9.9	5.9	17.1	2.3	71.1	6.2
Cl	2,096.7	125.0	11,373.3	466.1	12,896.7	187.2	13,306.7	85.0
Co	<LOD	-	730	225	1,400	110	893	290
Cr	236	17	319	99	278	30	294	42
Cu	1,647	263	3,547	1,077	4,063	1,175	1,737	172
Fe	56,833	11,760	60,333	5,090	56,100	872	29,467	3,265
Hf	ND	-	ND	-	ND	-	ND	-
K	7,967	351	9,340	79	9,257	119	5,940	79
Mg	8,120	14,064	10,577	18,319	12,687	21,974	<LOD	-
Mn	283	23	710	200	637	38	537	134
Mo	< LOD	-	203	10	53	6	53	6
Nb	0.0	0.0	185.0	0.0	20.0	0.0	0.0	0.0
Ni	207	52	212	51	274	103	201	15
P	277	21	677	588	927	93	697	46
Pb	1,501	1,656	820	312	764	115	1,079	81
Pd	< LOD	-	< LOD	-	< LOD	-	< LOD	-
Rb	< LOD	-	< LOD	-	< LOD	-	< LOD	-
S	3,847	187	28,393	1,058	29,597	497	39,573	1,410
Sb	143	15	331	10	93	21	97	49
Se	< LOD	-	< LOD	-	< LOD	-	< LOD	-
Si	336,610	11,437	134,807	9,533	115,150	3,270	75,770	3,193
Sn	33	6	297	31	117	6	117	67
Ta	ND	-	ND	-	ND	-	ND	-
Ti	1,223	50	8,850	858	10,610	52	8,760	1,220
V	< LOD	-	73	64	37	64	40	69
W	< LOD	-	70	121	< LOD	-	< LOD	-
Zn	7,017	464	5,667	430	6,630	985	551	1,079
Zr	150	0	241	859	203	15	163	169

Table S14: Mass fraction of all elements analysed in the glass fraction of the raw and aged BA in [mg/kg dry matter]; LOD: limit of determination; ND: not determined

Element	*Raw BA*		*Aged BA*	
	Mean	SD	Mean	SD
Ag	6.8	6.0	20.0	0.0
Al	976	62	1,750	400
As	24.8	9.2	<LOD	-
Au	<LOD	-	<LOD	-
Ba	735.1	143.3	886.7	30.6
Bi	<LOD	-	<LOD	-
Ca	79,061	4,857	299,567	17,043
Cd	0.5	0.0	3.7	2.2
Cl	3,535.8	2,267.9	19,040	1,079
Co	<LOD	-	3,557	225
Cr	10	2	55	9
Cu	1,005	707	341	247
Fe	1,823	421	5,943	4,229
Hf	ND	-	ND	-
K	6,691	655	8,097	483
Mg	6,555.1	11,353.8	<LOD	-
Mn	<LOD	-	943.3	102.6
Mo	8.1	0.8	63.3	5.8
Nb	5.6	1.3	23.3	5.8
Ni	6	2	22	3
P	358.6	33.8	930.0	79.4
Pb	48	24	112	46
Pd	4.2	3.6	<LOD	-
Rb	20	3	<LOD	-
S	5,170	1,830	54,717	2,880
Sb	81.1	11.7	106.7	11.5
Se	<LOD	-	<LOD	-
Si	294,851	38,316	74,700	2,926
Sn	37.4	9.0	143.3	11.5
Ta	ND	-	ND	-
Ti	1,185.4	104.4	14,953.3	1,104.3
V	<LOD	-	110.0	110.0
W	<LOD	-	<LOD	-
Zn	136	23	1,156	470
Zr	147	5	153	6

Table S15: Concentration of metallic aluminium in the grain sizes below 4 mm of the raw BA, determined by soda attack method

Grain size	Share	Mean	SD
2-4 mm	10.0%	2.11%	0.91%
1-2 mm	7.4%	1.44%	0.22%
0,063-1 mm	11.8%	0.67%	0.03%
< 0,063 mm	1.0%	0.08%	0.02%
< 4 mm		1.32%	0.09%
< 2 mm		0.93%	0.02%
< 1 mm		0.63%	0.00%

Table S16: Concentration of metallic aluminium in the grain sizes below 4 mm of the aged BA, determined by soda attack method

Grain size	Share	Al mean	Al sd
2-4 mm	11.7%	1.67%	0.63%
1-2 mm	9.3%	0.79%	0.05%
0,063-1 mm	10.4%	0.20%	0.02%
< 0,063 mm	0.4%	0.10%	0.01%
< 4 mm		0.91%	0.07%
< 2 mm		0.47%	0.01%
< 1 mm		0.20%	0.00%

Table S17: Share of the mineral content of the metals in the raw and aged MSWI BA

Grain size fraction	Al		Fe		Cu		Zn		Cr		Ni	
	raw	aged	raw	aged	raw	aged	raw	aged	raw	aged	raw	aged
> 31.5 mm	92%	94%	4%	8%	23%	19%	6%	9%	5%	5%	2%	2%
16-31.5 mm	55%	71%	27%	27%	26%	18%	44%	43%	6%	9%	6%	11%
8-16 mm	48%	67%	42%	29%	25%	10%	46%	48%	19%	47%	3%	2%
4-8 mm	53%	52%	64%	52%	19%	10%	66%	73%	39%	41%	39%	29%
2-4 mm	0%	35%										
1-2 mm	55%	68%										
0.063-1 mm	74%	90%										
< 0.063 mm	95%	95%										
> 4 mm	66%	74%	31%	26%	23%	15%	36%	39%	16%	25%	10%	9%
total	60%	71%	21%	18%	16%	10%	25%	26%	11%	17%	7%	6%

S.5.4 Leaching concentrations

Table S18: Leaching concentrations in the mineral fraction above 4 mm of the raw BA; LOD: limit of determination

Parameter	Unit	> 31.5 mm		16 - 31.5 mm		8 - 16 mm		4 - 8 mm	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
pH value	-	10.3	0.0	10.5	0.4	10.8	0.4	10.5	0.2
Conductivity	µS/cm	1228.9	361.1	1018.8	124.9	1730.2	54.6	2449.0	88.8
Cl^-	mg/l	246.3	103.6	153.7	23.8	207.2	22.4	280.5	7.5
SO_4^{2-}	mg/l	198.2	26.1	169.4	23.7	522.8	79.9	998.6	54.0
As	µg/l	<LOD	-	0.7	0.0	<LOD	-	0.8	0.0
Cd	µg/l	0.7	0.0	0.5	0.0	<LOD	-	0.3	0.0
Cr	µg/l	31.1	11.6	15.9	17.4	11.7	11.9	4.3	0.0
Cu	µg/l	3.5	0.6	3.6	1.8	12.8	5.2	20.7	5.4
Hg	µg/l	<LOD	-	<LOD	-	<LOD	-	<LOD	-
Ni	µg/l	<LOD	-	<LOD	-	<LOD	-	<LOD	-
Pb	µg/l	<LOD	-	2.8	0.0	1.3	0.0	<LOD	-
Zn	µg/l	8.0	1.3	11.8	1.8	13.1	5.4	139.1	119.4

Table S19: Leaching concentrations in the mineral fraction below 4 mm of the raw BA; LOD: limit of determination

Parameter	Unit	2 - 4 mm		1 - 2 mm		0,063 - 1 mm		< 0,063 mm	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
pH value	-	11.1	0.0	11.6	0.0	12.0	0.1	11.8	0.1
Conductivity	µS/cm	3320.0	70.7	4060.0	4060.0	5640.0	28.3	7565.0	1011.2
Cl^-	mg/l	395.0	21.2	505.0	7.1	595.0	7.1	1150.0	70.7
SO_4^{2-}	mg/l	1300.0	0.0	1050.0	70.7	1350.0	70.7	1350.0	70.7
As	µg/l	3.0	0.0	1.0	0.0	<LOD	-	1.0	0.0
Cd	µg/l	0.5	0.0	0.6	0.1	0.5	0.1	1.9	0.9
Cr	µg/l	2.5	0.7	70.0	4.2	176.5	0.7	243.5	47.4
Cu	µg/l	35.5	0.7	54.0	4.2	53.0	7.1	286.5	160.5
Hg	µg/l	<LOD	-	<LOD	-	<LOD	-	<LOD	-
Ni	µg/l	<LOD	-	<LOD	-	<LOD	-	3.0	1.4
Pb	µg/l	32.0	0.0	26.5	2.1	93.5	3.5	100.0	67.9
Zn	µg/l	52.5	4.9	78.5	0.7	38.2	0.0	298.5	227.0

Table S20: Leaching concentrations in the mineral fraction above 4 mm of the aged BA; LOD: limit of determination

Parameter	*Unit*	*> 31.5 mm*		*16 - 31.5 mm*		*8 - 16 mm*		*4 - 8 mm*	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
pH value	-	10.1	0.2	10.8	0.2	10.5	0.1	10.7	0.0
Conductivity	µS/cm	1141.8	380.4	964.3	125.0	2063.9	220.6	2452.0	177.5
Cl-	mg/l	102.9	34.4	83.5	9.2	210.8	34.7	285.2	15.4
SO42-		337.2	168.9	150.9	41.6	751.9	94.4	859.2	97.8
As	µg/l	0.5	0.6	<LOD	-	1.2	1.2	1.7	0.0
Cd		0.0	0.0	0.3	0.2	0.2	0.2	0.2	0.1
Cr		4.6	6.5	18.0	0.8	23.0	4.1	52.3	8.3
Cu		4.9	2.1	4.9	2.2	50.9	18.4	62.1	6.8
Hg		<LOD	-	<LOD	-	<LOD	-	<LOD	-
Ni		<LOD	-	0.4	0.5	<LOD	-	<LOD	-
Pb		0.1	0.2	2.1	2.1			0.5	0.7
Zn		49.8	30.4	88.9	88.9	53.4	12.3	47.8	4.7

Table S21: Leaching concentrations in the mineral fraction below 4 mm of the aged BA; LOD: limit of determination

Parameter	*Unit*	*2 - 4 mm*		*1 - 2 mm*		*0,063 - 1 mm*		*< 0,063 mm*	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
pH value	-	10.6	0.0	10.5	0.0	10.7	0.0	10.4	0.0
Conductivity	µS/cm	2800.0	141.4	3465.0	35.4	3215.0	1067.7	6390.0	113.1
Cl-	mg/l	340.0	0.0	520.0	42.4	500.0	226.3	1250.0	70.7
SO42-		985.0	21.2	1000.0	0.0	890.0	297.0	1700.0	0.0
As	µg/l	8.5	7.8	3.5	2.1	0.5	0.7	2.5	0.7
Cd		0.4	0.1	0.6	0.1	0.5	0.2	1.9	0.2
Cr		48.0	8.5	150.5	7.8	184.5	65.8	987.5	74.2
Cu		61.5	6.4	97.0	1.4	134.0	48.1	451.5	13.4
Hg		<LOD	-	<LOD	-	<LOD	-	<LOD	-
Ni		<LOD	-	1.0	0.0	2.0	1.4	4.0	0.0
Pb		<LOD	-	4.5	4.9	<LOD	-	<LOD	-
Zn		43.5	2.1	62.5	20.5	29.5	2.1	108.0	110.3

Table S22: Leaching concentrations in the glass of the raw and aged BA; LOD: limit of determination

Parameter	*Unit*	*Raw BA*		*Aged BA*	
		Mean	SD	Mean	SD
pH value	-	10.5	0.1	10.6	0.1
Conductivity	µS/cm	366.5	12.0	459.0	1.4
Cl^-	mg/l	19.0	0.0	30.5	3.5
SO_4^{2-}	mg/l	65.0	0.0	92.5	10.6
As	µg/l	3.0	1.4	0.5	0.7
Cd	µg/l	<LOD	-	<LOD	-
Cr	µg/l	23.0	21.2	20.5	3.5
Cu	µg/l	3.5	0.7	8.0	0.0
Hg	µg/l	<LOD	-	<LOD	-
Ni	µg/l	<LOD	-	<LOD	-
Pb	µg/l	<LOD	-	<LOD	-
Zn	µg/l	13.5	2.1	112.0	42.4

S.5.5 Resource potentials

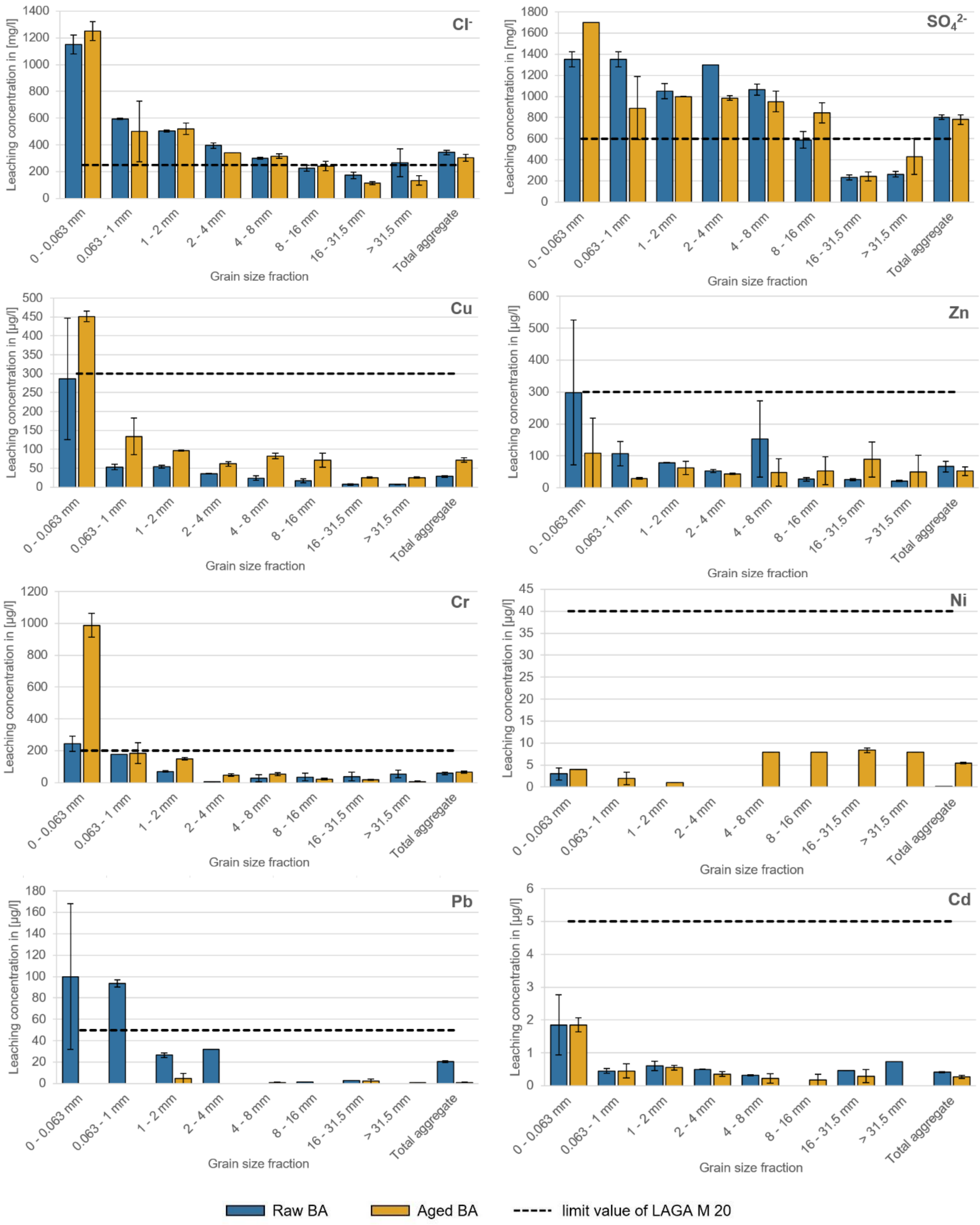

Figure S8: Leaching concentrations for evaluation of the utilisable resource potential as construction material in contained structures (such as road subbase layers) under the regulation of LAGA M 20

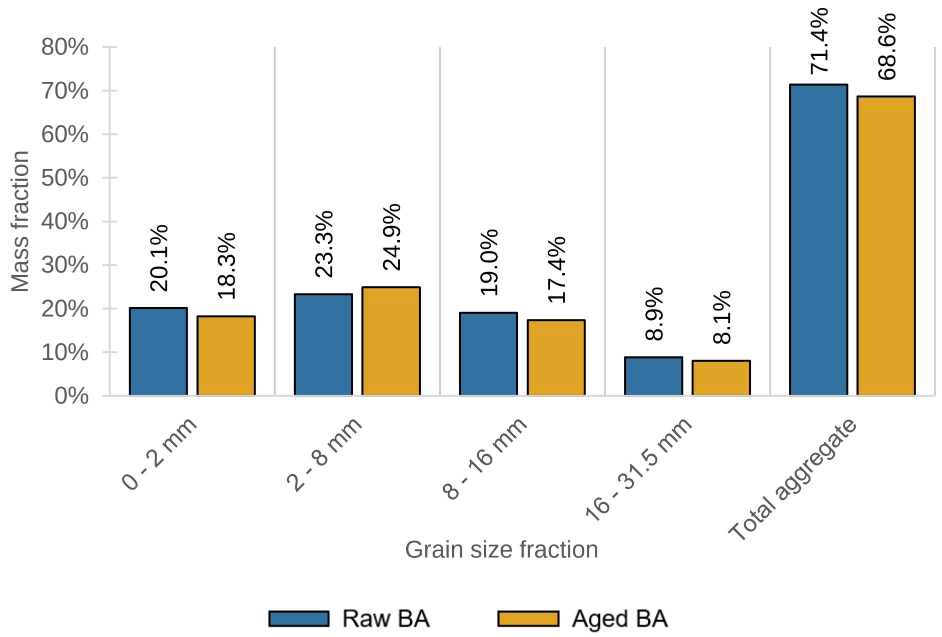

Figure S9: Particle size distribution of the Fuller-curve mixture

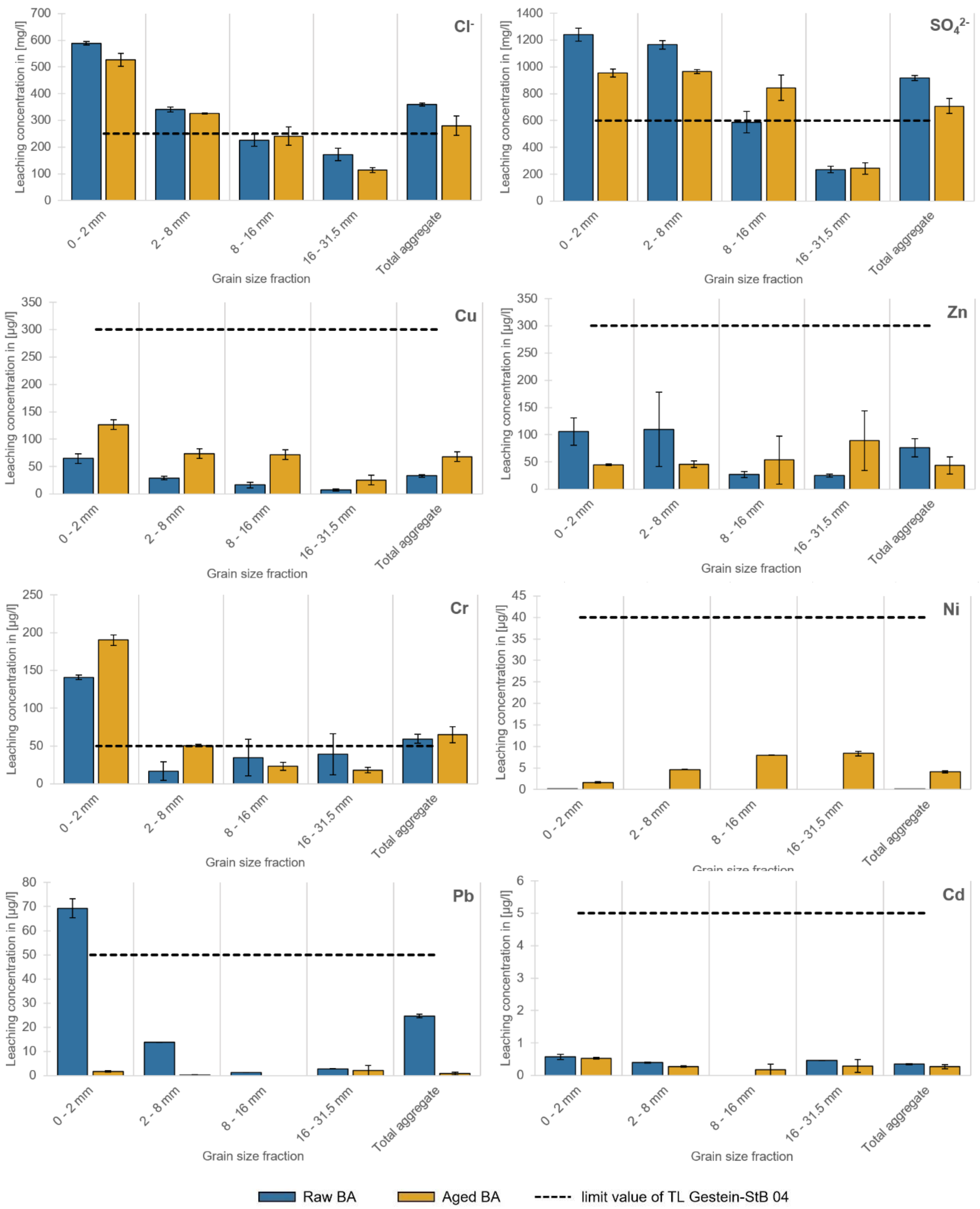

Figure S10: Leaching concentrations for evaluation of the utilisable resource potential as construction material in contained structures (such as road subbase layers) under the regulation of TL Gestein-StB 04

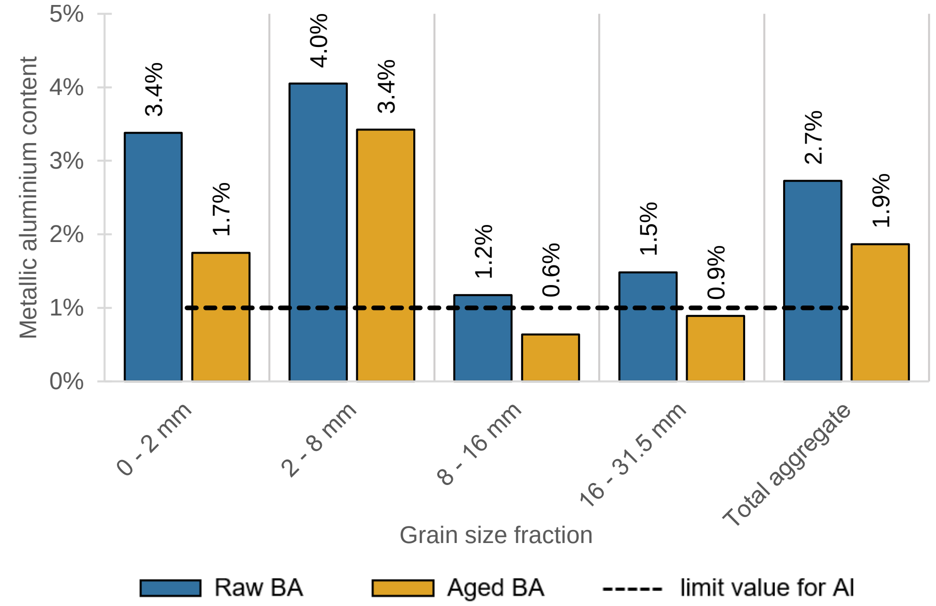

Figure S11: Content of metallic aluminium in the Fuller-curve mixture

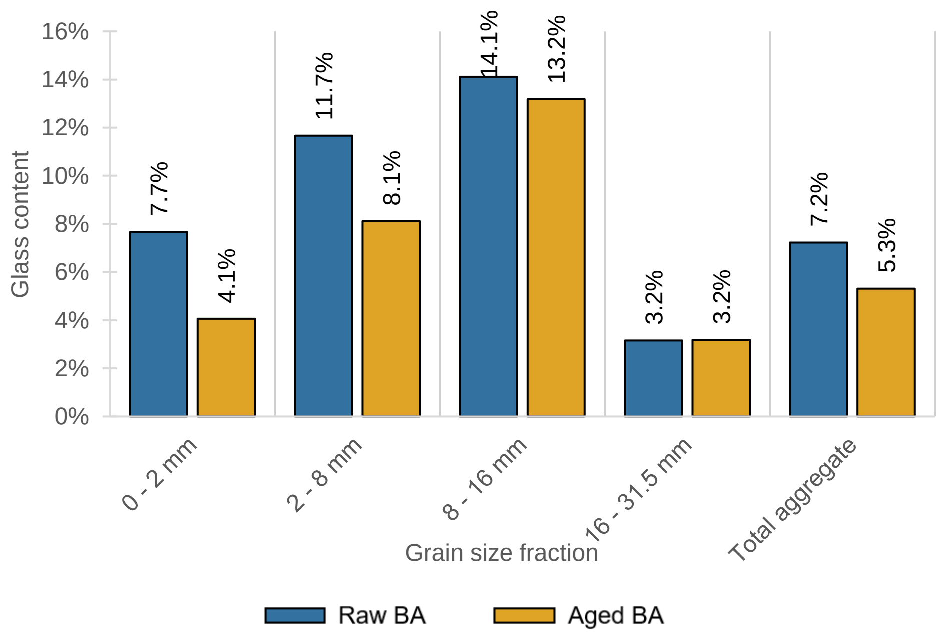

Figure S12: Glass content in the Fuller-curve mixture

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