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Case Study on Secondary Building Materials for a Greener Economy

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Abstract: Half of global material consumption involves mineral material. The circularity is still low so that the enhanced use of secondary building material is required to close loops. Three different secondary building materials are discussed based on exemplary research results: construction and demolition waste (C&D waste), soil-like material, and incineration bottom ash (IBA). Focus was placed on the environmental compatibility of the materials examined mainly by standardized leaching tests. C&D waste was investigated after a wet treatment using a jigging machine, and soil-like material and IBA were characterized with respect to their material composition. Their environmental compatibilities in particular were studied using standard leaching tests (batch tests and column tests). It was concluded that soil-like material can mostly be utilized even when the precautionary limit values set are exceeded by a factor of less than two. For C&D waste, the fine fraction below 2 mm and the content of brick material is problematic. IBA fulfills quality level "HMVA-2" following German regulations. Improved levels of utilization might be achievable with better treatment technologies.

Keywords: soil-like material; construction and demolition waste; incineration bottom ash; leaching; circular economy

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1. Introduction

The world's material consumption increased from 71,000 million metric tons in the year 1900 to 101,500 million metric tons in 2021 [1,2]. Responsible for half of this tonnage are mineral materials, mainly used in the building and construction industry, making them the largest resource extracted globally [3]. Their main use is as aggregates in infrastructure projects and the production of concrete [4]. The natural resources for sand and gravel are not scarce, and the specific energy consumption for the production of aggregates is dependent on the processing route (e.g., higher for the crushing of stone and lower for the extraction of river aggregates) in the range of 11–38 MJ/ton only [5–12]. For comparison, the specific energy consumption figures for the production of steel and cement are 13,400 and 3040 MJ/ton, respectively [9]. Although the specific energy consumption for aggregate production is low, the environmental impact is still high just due to the extremely large material flows. It has been found that the energy demand for the production of recycled aggregates is even slightly higher (20–25%) than that of natural material [8,9].

However, the substitution of natural aggregates by recycled material at least saves natural resources and supports a circular economy. Construction and demolition waste (C&D waste, European waste catalogue code EWC 17) is the most important source for secondary building materials, with 221 million metric tons being consumed in Germany in 2020 [13]. The amount of concrete, bricks, tiles, and ceramics (EWC 17 01) was 61 million metric tons in the year 2020 [13]. The steel recovered from recycled aggregate concrete structures is advantageous under all circumstances [5]. The supply of recycled mineral material cannot cover the demand for aggregates completely. For example, the demand for fine and coarse aggregates in Germany was 585 million metric tons in the year 2020;

however, only 13.2% were produced by recycling measures [14]. The applied technologies for the treatment of C&D waste were reviewed recently [15].

A further sub-group within C&D waste is soil-like material such as waste with EWC code 17 05 04 (soil and stones) or 17 05 07 (dredging spoil). In Germany the amount of this category was 129 million metric tons (year 2020, [14]). Most of this waste was recycled and utilized, while only 14.3% was disposed of to landfills. Compared to natural soil, soil-like materials exhibit secondary raw materials and comprise (a) excavated and/or anthropogenically influenced soils, (b) dredged material from earthworks and waterway construction measures, (c) soils treated to remove pollutants, and (d) soils produced from excavated soil and other material such as compost. Soil-like materials can be contaminated with pollutants depending on their previous use or origin. The potential applications of soil-like materials depend not only on the content of pollutants in the solid matter, but also on their potential release into the environment.

Another source for secondary building materials is the bottom ash of municipal solid waste incineration (MSW incineration bottom ash, herein abbreviated as IBA, EWC code 19 01 12). Throughout Europe, the annual production of IBA is 19 million metric tons. In Germany, the figure is 6.05 million metric tons [16]. At around 25%, IBA represents the largest residue fraction in thermal waste treatment. It consists of solid phases already contained in municipal waste, such as pieces of glass, ceramics, ash, and metals (ferrous and non-ferrous metals), as well as new phases formed during the combustion process [17]. The five main chemical elements in bottom ash are Si, Ca, Fe, Al, and Na. While Si and Ca are bound as oxides and silicates, Al and Fe also occur in their elemental form. Na is additionally present as chloride, while Ca is as sulfate [18]. The treatment of IBA is focused on the recovery of mineral material (app. 90% of the IBA) and elemental metals (ferrous and non-ferrous, app. 10%). Details regarding the treatment processes have been discussed in depth elsewhere [19,20]. The amounts of C&D waste and IBA in Germany are displayed in Figure 1.

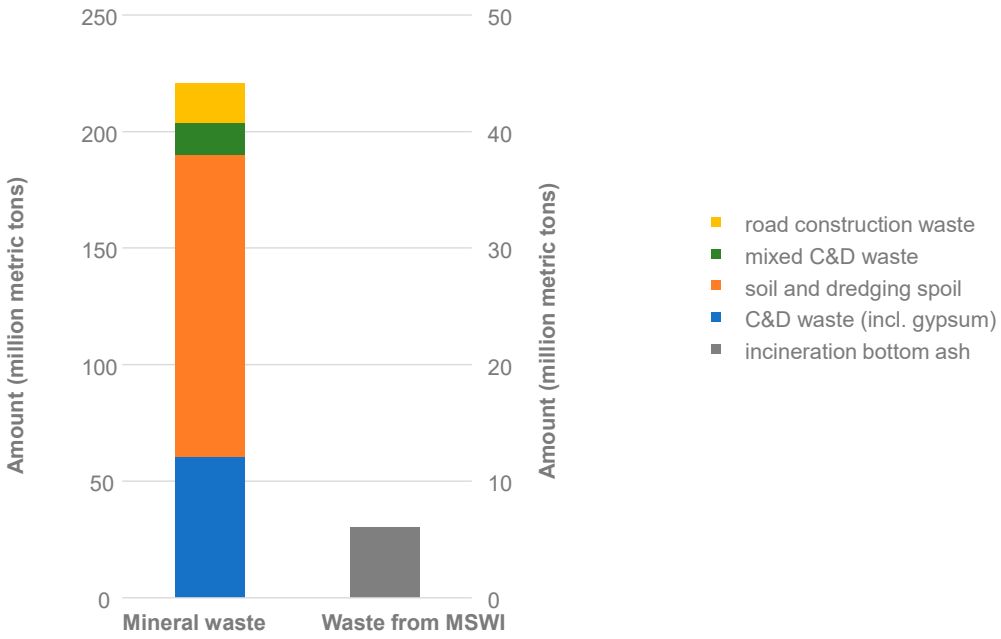

Figure 1. Volume of secondary building materials in Germany (data for 2020) [14,16]. Note the different axes for mineral waste (left, 0–250) and IBA (right, 0–50).

The German government is developing a National Circular Economy Strategy that will combine existing raw materials policies. The strategy will bring objectives and measures for circular economy and resource conservation together. With the Secondary Building Material Decree (German: Ersatzbaustoffverordnung EBV), a legal framework was adopted

in Germany describing the requirements for the utilization of the above mentioned waste materials [21]. Limit values for leachate concentrations of inorganic and some organic pollutants have been set, as well as for the total content of polycyclic aromatic hydrocarbons (PAH) and polychlorinated biphenyls (PCB) for certain waste materials (soil-like material and recycled aggregates). In the case of soil-like materials, limit values for the total content of heavy metals have also been set. Depending on the leachate concentrations or total content, different quality levels of the secondary building materials have been defined (e.g., "RC-1", "RC-2", "RC-3" for recycled aggregates or "HMVA-1" and "HMVA-2" for IBA), enabling more high-grade utilization pathways. "HMVA" is derived from the German word for IBA ("Hausmüllverbrennungsasche")

The use of secondary building materials depends on several enabling factors and barriers, many of which have been discussed in detail elsewhere [22]. This paper questions to what extent secondary building materials can help to lower the environmental impact of material use and support a circular economy using C&D waste, soil-like materials, and IBA as examples, thereby highlighting smart materials.

2. Materials and Methods

2.1. C&D Waste

In the recycling processes of C&D, waste crushers and sieves come into operation. The resulting fine fraction, crushed sand, is often excluded from utilization as an aggregate for concrete production [9] and is instead used for lower-ranked applications such as sub-base layers, dams, and walls. The reasons for this include the residual attachments of the cement matrix, adverse grain shape, and comparatively higher content of hazardous substances (e.g., PAHs or sulfates) [23]. For the study presented in this article, two materials, from construction and demolition, were investigated: crushed sand (CD-1) and material from a C&D waste treatment facility in Berlin (CD-2).

One material (CD-1) was delivered from a company in the C&D waste recycling sector in southern Germany. It was a contaminated crushed sand that could not be recycled economically and was a by-product of the crushing process—a recycled material with the EWC code 17 01 07 with app. 35% of the total material being contaminated. The contaminant content here was so high that landfilling was necessary. The material was processed in a pilot scale wet treatment plant with a jig for density separation (Alljig P400/600 × 800, Company Allmineral, Duisburg, Germany) [23]. The objective was to enrich the contaminants in a marginal fine fraction and to reach quality level RC-1 for the heavy fraction. Target impurities were sulfates and PAHs. Leachates were prepared using column percolation according to DIN 19528:2009–01 up to a liquid to solid (L/S) ratio of 2 L/kg. Analyses of PAH and sulfate within the leachates and the solids was performed using GC-MS (Agilent 5973 with quadrupol GC/MS detector) and ion chromatography (Dionex Integrion, Thermo Fisher Scientific, Dreieich, Germany).

The second material (CD-2) was a typical urban construction and demolition waste. It was processed on a mobile pilot scale jig (Triple A, Company AGS, Schwentinental, Germany [24]), generating a light fraction and a heavy fraction. No chemical analyses were performed with the material. Manual sorting of the heavy fraction <32 mm into the categories mortar, stones, glass, bricks, ceramics, and metals was performed and evaluated.

2.2. Soil-like Materials

The utilization of soil-like material, according to the German Soil Protection Decree (part of the legal framework [21]), depends on whether one complies with the limit values for total content and leachates. Precautionary limit values based on total contents are defined for numerous organic and inorganic contaminants. Regarding the requirements for the utilization of soil-like materials, analyses of leachates are only necessary if the precautionary limit values have been exceeded.

For PAHs, as the most abundant and ubiquitous organic pollutants, we investigated whether exceeding the precautionary value for PAHs by a factor of no more than two while

complying with the given leaching limits could be viable and enable the utilization of more soil-like materials without interfering with the good status of soils. In the course of this investigation, more than 20 soil-like materials were analyzed for PAHs in the solid matter and eluate [25,26]. Different soil-like material types containing PAHs and representing large material streams were collected and abbreviated as follows:

- Soils from urbanized areas (STB) and, in some cases, their subsoils (UB/STB);
- Topsoils from roadside areas in the form of banquet peelings (BSG);
- Dredged sediments from water bodies, partly with marine influence (BAG);
- Admixture of soil-like material and mining waste (BER);
- Alluvial soils with suspected contamination from industry (AUE).

Some inorganic parameters, such as metals and sulfate, were considered and analyzed as well, but PAHs were the focus of the study.

2.3. Incineration Bottom Ash (IBA)

IBA was sampled at two waste incineration plants in Germany. Sample size was in the range of 1–2 tons. The leaching behavior was studied using batch tests according to DIN 19529:2015-12 (examination of the leaching behavior of inorganic and organic substances at a liquid to solid ratio of 2 L/kg) as a function of storage time. Further, the uptake of CO_2 was measured via the determination of the carbonate content (i.e., the addition of HCl to the solid sample in a closed vessel and measurement of the resulting pressure increase from the released CO_2). The leaching tests were performed over a period of 102 (IBA-1) and 281 (IBA-2) days, respectively.

2.4. Analytical Methods

PAH content analyses were performed following DIN EN 16181: 2019-08 (now DIN EN 17503) (determination of PAH in solid matrices by GC), and PAHs in eluates were analyzed using DIN 38407-39: 2011-09 (the determination of selected PAHs was completed using gas GC-MS). Heavy metal analyses were performed following DIN EN 13657/DIN ISO 22036 (digestion for the subsequent determination of aqua regia soluble portion of elements in waste) for solids and DIN EN ISO 11885 (determination of selected elements by ICP-OES) for eluates using ICP-OES (I-CAP 7000, Thermo Fisher, Dreieich, Geermany). ICP-MS following DIN EN ISO 17294-2 (I-CAP Q, Thermo Fisher, Dreieich, Germany) was applied when the concentrations of substances were close to the relevant threshold values or below the detection limit of ICP-OES.

To measure the eluate concentration, column tests, according to DIN 19528:2009-01 (percolation method for the joint examination of the leaching behavior of inorganic and organic substances) at a liquid/solid ratio (L/S) of 2 L/kg and batch tests according to DIN 19529:2015-12 also at a liquid/solid ratio (L/S) of 2 L/kg, were performed in parallel in order to evaluate the comparability of the results for these two leaching test types.

3. Results

Three rather different materials were studied in the present article. However, recycled aggregates, soil-like materials, and incineration bottom ash are expected to be used as secondary building materials when certain quality levels are achieved. Often, a treatment process is necessary to separate (and concentrate) contaminants and other impurities or, as in the case of the soil-like material here, an analytical assessment of the applicability.

3.1. Sorting of C&D Waste

The applied treatment process in the pilot plant [23] for the crushed sand (material CD-1, see above) produced two separate material streams via density separation. The largest fraction, with 89 w%, was the heavy product fraction with reduced impurity contents. The light fraction, in turn, exhibited impurity contents that increased accordingly and comprised 11 w%. The key results of the applied process regarding the analysis of the heavy fraction were a 56% reduction in PAHs and a 29% reduction in sulfates within

the solid product. A significant improvement was also achieved regarding the eluate concentrations of sulfate, which was reduced by 31% (from 1895 to 1311 mg L^{-1}). However, the limit value for quality class RC-1 is 1000 mg L^{-1}. Leaching of PAH was slightly reduced but, with 8.4 µg L^{-1}, is still above the limit value for RC-2 of 8 µg L^{-1}. However, the scattering of the leaching values is 3.7 µg L^{-1}.

The sorting of material CD-2 with the mobile pilot scale jigging machine Tripe A [24] separated a light fraction with a high content of organic material (loss on ignition at 600 °C 12.1%). The sieving curve of the heavy fraction is displayed in Figure 2.

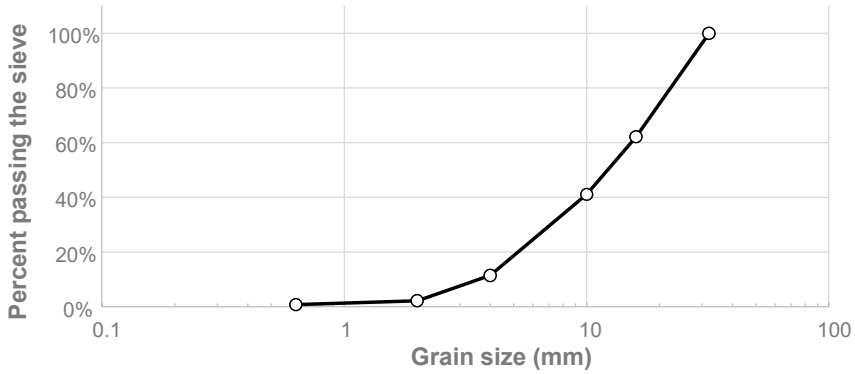

Figure 2. Sieving curve of the heavy fraction of material CD-2.

The grain size fraction 16–32 mm of material CD-2 was sorted manually in six different categories (bricks, mortar, stones, glass, metals, and ceramics), see Figure 3.



Figure 3. Photos of the individual material groups and screen fractions (from top left to bottom right: >16 m unsorted, >16 mm bricks (25.8%), >16 mm mortar (50.6%), >16 mm stones (14.2%), >16 mm glass and metals (0.4%), and sieving fractions <0.63, <2 and <4 mm together). Material group "ceramics" (9%) not illustrated. (Photographs by F.-G.S.).

The findings from the examination of material CD-1 and CD-2 outline the main obstacle with C&D waste recycling. The fine fraction from crushing often contains elevated concentrations of contaminants that cannot be easily separated even by sophisticated treatment processes such as jigging. Therefore, the fine fraction of C&D waste recycling is often not taken into account for concrete production [9].

According to guidelines from the German Committee for Reinforced Concrete (DAf-Stb [27]), two possible types of recycled aggregates are defined: In type 1, more than 90% of the material must originate from concrete or from natural stones. However, this value is lowered to 70% in type 2, thus allowing a 30% content of brick material. C&D waste can hardly be separated to yield recycled aggregate type 1 when materials from concrete structures are mixed with those from brick buildings. However, the 30% limit for brick material in type 2, would be maintained.

3.2. Assessment of PAH-Containing Soil-like Material

The amended German Federal Soil Protection and Contaminated Sites Decree [21], which will be enforced from August 2023 onwards, contains new requirements regarding the application of soil-like material outside of a rootable soil layer. It is intended to enable the utilization of soil-like materials containing regulated substances in concentrations between the single and double precautionary values, provided that the limit values for the eluate are complied with. The aim of a research project by Kalbe et al. [26] was to fill data deficits for soil-like materials that meet the aforementioned criteria to promote circular economy and the conservation of natural resources. Different soil-like material types containing PAHs were investigated (see Section 2.2). A major challenge in sample acquisition was the relatively narrow target range of the PAH content, which was between 3 and 6 mg/kg of dry matter (concentration between precautionary limit value and its double value)—considering a high measurement uncertainty at this concentration level mainly caused by the laborious sample preparation steps before analysis [28]. Finally, twelve of the twenty-three investigated materials had a total PAH content in the desired range (see Table 1 and Figure 4). From the twelve soil-like materials inside of the desired PAH content range, only one material from an urban source (STB12) failed the to achieve the leaching limit value for PAH, meaning that further utilization of the material is excluded. This could be due to fire exposure, as indicated by the distribution pattern of PAHs in urban soil.

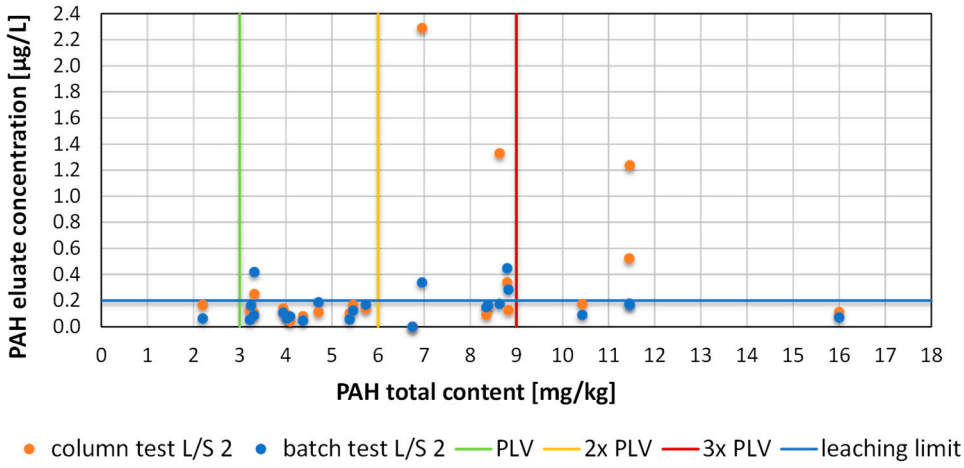

Figure 4. Graphical overview of the utilization potential of the soil-like materials investigated, considering PAHs (PLV = precautionary limit value for total content).

Comparing column and batch tests, larger differences for the eluate concentrations of the sum of PAHs occurred only for materials whose total content was above the target content range (i.e., above 6 mg/kg, see Figure 4). Consideration of the additional inorganic parameters measured (limit values for metals) led to the exclusion of another five materials regarding the recovery potential (Table 1). For sulfate, only a limit value for the eluate has to be taken into account. All materials which exceeded the limit value for sulfate (BAG 5 to 8, STB 3 and 14, UB/STB 1, 2, and 5) exhibited other exceedances for metals already (see Table 1).

Table 1. Overview of the utilization potential of the soil-like materials investigated. Color-coding refers to traffic light logic (PLV = precautionary limit value for total content).

Soil-like Material	∑16 EPA PAH Total Content [mg/kg]	∑15 EPA PAH * Column Test L/S 2 [µg/L]	∑15 EPA PAH * Batch Test L/S 2 [µg/L]	Evaluation of Potential for Utilization		
				PAH	Further Cations	Overall
AUE 4	5.73	0.14	0.17			
AUE 5	4.38	0.08	0.05			
AUE 6	5.40	0.10	0.06			
BAG 5	8.34	0.09	0.15		Ni, **Zn**, Mo	
BAG 6	10.43	0.17	0.09		Hg, **Zn**, Sb, Mo	
BAG 7	3.30	0.11	0.09		**Ni**, *Zn*, **Mo**	
BAG 8	5.46	0.16	0.12		**Pb**, **Cd**, Cu, **Ni**, Hg, *Zn*, **Mo**	
BER 1	4.03	0.09	0.06		*Cr*, **Cu**, **Ni**, *Hg*, **Zn**, **Sb**, *Mo*, **Se**, *V*, **Sn**	
BER 2	2.19	0.17	0.06		**Se**	
BSG 1	6.96	2.29	0.34		**Cr**, *Ni*, Sb	
BSG 2	3.95	0.14	0.11		*Ni*, Sb	
STB 2	8.39	0.16	0.16		**Pb**, Ni, *Zn*, Sb	
STB 3	16.00	0.11	0.07		**Pb**, **As**, **Cd**, **Cu**, **Pb**, **Tl**, **Sb**, *Se*	
STB 4	8.84	0.13	0.28			
STB 6	3.25	0.16	0.16			
STB 7	3.23	0.13	0.05			
STB 12	3.32	0.25	0.42		**Cu**, Sb, **Se**	
STB 14	11.44	0.52	0.18		**Pb**, **Se**	
STB 16	4.10	0.04	0.08		**Zn**	
STB 21	4.71	0.11	0.19			
UB/STB 1	8.64	1.33	0.17		Cu, *Ni*, Sb	
UB/STB 2	11.45	1.24	0.17		Cu, *Ni*, Sb	
UB/STB 5	8.81	0.34	0.45		**As**, **Pb**, **Cd**, **Cr**, **Cu**, **Ni**, **Zn**, Sb, **Co**, **Mo**, **V**, **Sn**	

Legend			
	<2× PLV	leaching limit value kept	utilization allowed
	up to 3× PLV		
	>3× PLV	leaching limit value exceeded	utilization excluded

* naphthalene is not included in leaching analyses

exceedance of total content/lexceedance of leaching limit
exceedance of total content and leaching limit

Overall, as expected, the single PAH compounds with medium molecular sizes (phenanthrene to chrysene) were the most abundant compounds in the eluates for almost all soil-like materials, which is related to the lower stability of compounds with smaller molecules and lower solubility of compounds with larger molecules (Figure 5). Fluoranthene and pyrene most frequently had the highest individual concentrations in the eluates. Higher naphthalene concentrations were observed, particularly in eluates from alluvial soils (AUE) and materials containing tailings (BER). The eluate value for naphthalene was never exceeded for the materials in the target range for the total content of PAH. In the dredged materials (BAG), volatile PAHs were hardly present in the eluates. In the eluates obtained from banquet peeling materials (BSG), the more sparingly soluble PAHs, starting with benzo[b]fluoranthene, were proportionally more released compared to other materials. The benzo[a]pyrene concentrations in the eluates tested were very low and mostly below the analytical limit of quantitation.

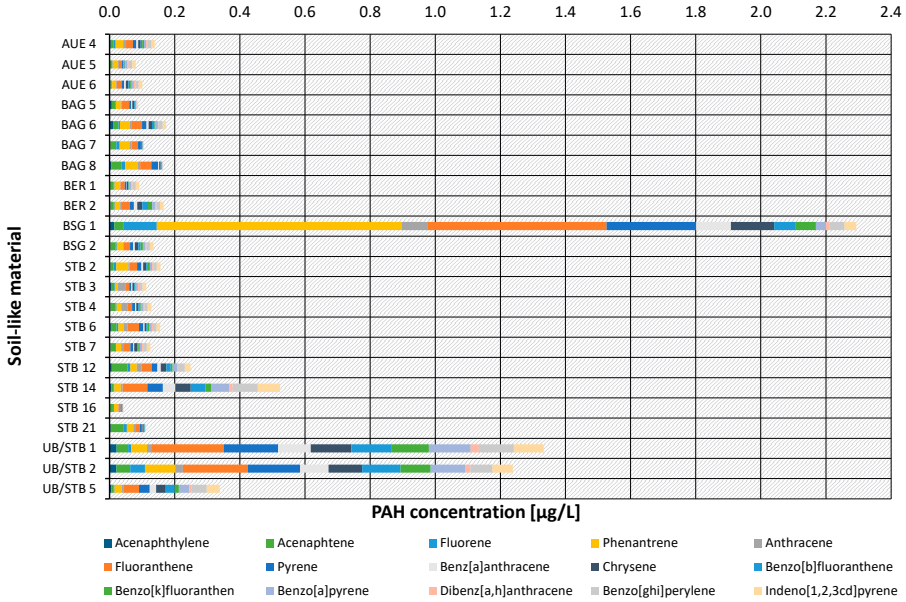

Figure 5. Distribution pattern of PAHs in column test eluates at L/S 2 L/kg of soil-like materials.

With regard to the type of the soil-like materials, dredged material and urban soils (in particular urban subsoils) are often not suitable for further recycling. Soil materials with proportions of tailings (BER) exhibit very specific pollutant inventories, mainly due to their respective origin, which does not allow for a general assessment of this material type based on the data obtained in this study. Of the two banquet peeling materials (BSG) examined in more detail, one material would be eliminated for utilization. Especially for the soils from urbanized areas (STB), urban subsoils (UB/STB), and dredged materials (BAG), the permitted sulfate concentration in the eluate was frequently and sometimes considerably exceeded, which could imply restrictions for the utilization of such material types and has to be examined on a case-by-case basis. Good prospects for an extension of the utilization options according to the new rules of the German Federal Soil Protection and Contaminated Sites Decree [21] can be observed, especially for alluvial soils (AUE).

3.3. Environmental Compatability of Incineration Bottom Ash (IBA)

Two quality levels for IBA are defined in the Secondary Building Materials Decree [21], "HMVA-1" and "HMVA-2", see Table 2. The classification is based on column percolation or batch tests at an L/S of 2 L/kg. IBA is usually extracted via a wet discharge system behind the incineration chamber. Then, ferrous and non-ferrous metal are separated with magnets and eddy current separators, respectively. Subsequently, the ash is stored for 6 weeks or more for the completion of aging reactions [19,20]. The aging reactions (uptake of CO_2 by CaO yielding $CaCO_3$, formation of hydraulic phases (CSH phases), corrosion of elemental metals) do not influence the electrical conductivity and the concentrations of chloride and sulfate in the standard leaching tests, but the pH of the leachates. Initially, with fresh IBA, high pH values of around 12.5 are measured. With progressing aging, the pH values decrease to values around below 11. Most heavy metal compounds exhibit a strong dependence on the solubility in the pH. If the solubility is high at high pH values due to the formation of metal hydroxo complexes $(Me(OH)_4^{2-}$ with Me as two-valent ion), the pH then decreases to a minimum around pH 6–8 [29]. This trend was observed in the long-term investigation of the leaching behavior of IBA, see Figure 6.

Table 2. Limit values for leaching c_i at L/S = 2 L/kg for the utilization of IBA. The release E_i can be calculated according to $E_i = c_i \times L/S$.

Parameter	HMVA-1	HMVA-2
pH	7–13	7–13
Electr. conductivity (µS cm^{-1})	2000	12,500
Chloride (mg L^{-1})	160	5000
Sulfate (mg L^{-1})	820	3000
Antimony (µg L^{-1})	10	60
Chromium (µg L^{-1})	150	460
Copper (µg L^{-1})	110	1000
Molydenum (µg L^{-1})	55	400
Vanadium (µg L^{-1})	55	150

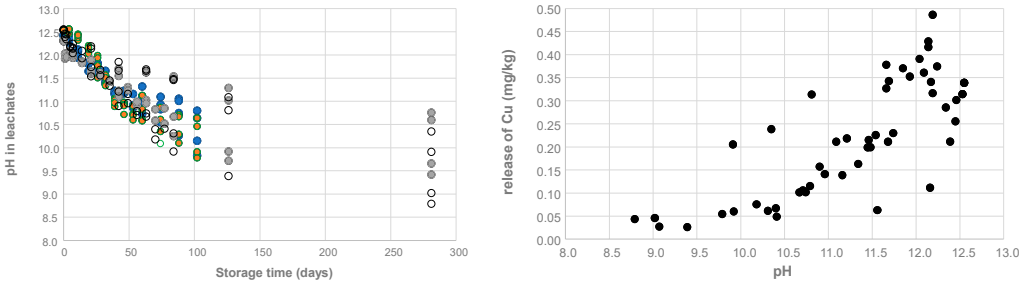

Figure 6. pH values in leaching tests according to DIN 19529 as a function of the storage time of IBA (**left**) whereby the differently colored points represent two sampling sites and two L/S ratios (2 and 10 L/kg). Release of Cu in mg/kg a s a function of the pH in leaching tests (**right**). The release E_{Cu} in mg/kg was calculated from concentrations c_i in mg/L by multiplication with 2 at an L/S = 2 L/kg.

The concentrations of vanadium and antimony depend on the concentration of Ca^{2+} ions. At high Ca concentrations, soluble calcium vanadates and antimonates are formed. The aging processes lead to lower Ca^{2+} concentrations due to the formation of stable $CaCO_3$. This behavior is described in detail elsewhere [30,31]. In the complete survey, no exceedance of the leaching limit values, according to the quality level for "HMVA-2", was observed. The values for "HMVA-1" were not reached simply due to the stringent values for chloride, sulfate, and electrical conductivity. These values could possibly only be reached with an advanced washing process.

As previously stated, $CaCO_3$ is formed during the aging process of IBA. CO_2 can be transported into an ash storage pile via atmospheric CO_2 or by CO_2 dissolved in rainwater. The carbonation of IBA has already been studied elsewhere [32–34]. In our studies, similar results were obtained, see Figure 7. The initial carbonate concentration was around 5%, increasing to maximum values of 9%. The experimental data were fitted using the solver module in MS Excel with the function $y(t) = y(0) + K_F\, t^{1/n}$, with y being the carbonate concentration, K_F as arbitrary constant, and t the storage time in days. Best fit was achieved with $K_{F'} = 0.36$ and $1/n = 0.49$. So, within 90 days, 0.32 mol CO_2 (13.9 g) could be sequestered per kg IBA. This is in the same order of magnitude as for recycled concrete aggregates, where values between 2.8 and 9.5 g CO_2 per kg material were found [9].

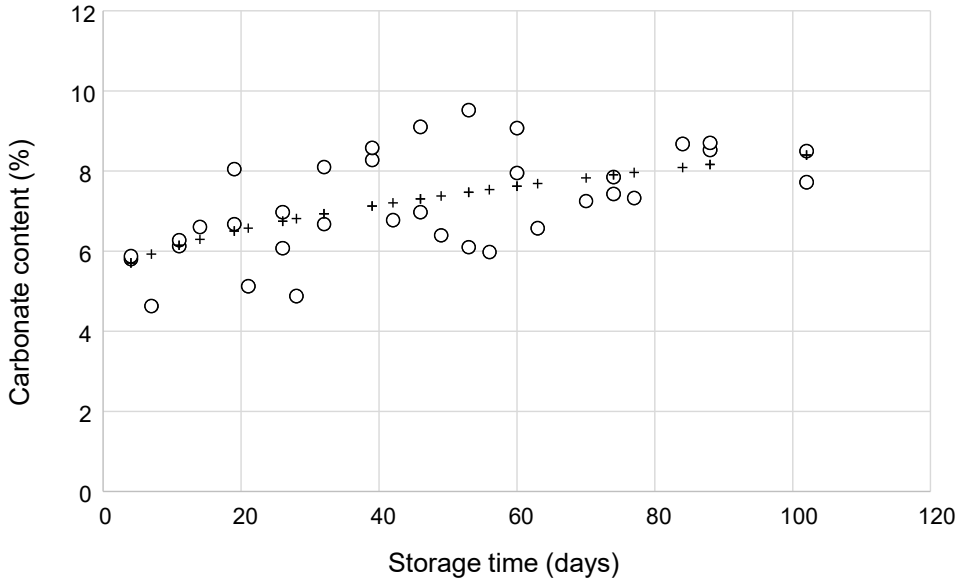

Figure 7. Content of carbonate in solid IBA samples as a function of the storage time. Experimental data are displayed as circles and fitted concentrations are displayed as crosses.

4. Discussion

The circularity of the global economy was at 7.2% in the year 2022. This is even lower than in the preceding years (2018: 9.1%, 2020: 8.6%) [35]. This is attributable to the continuously increasing world population, as well as rising material extraction and use. In Europe, the situation is better. The European Commission has decided on an action plan for measures focusing on sectors with a high potential for circularity, such as construction and building, in an attempt to generate less waste [36].

After long-lasting discussions, the Secondary Building Material Decree was finally penned in 2021 in Germany [21], and will be enforced from August 2023 onwards. For the first time, the requirements for the utilization of mineral waste will be uniformly defined for all 16 German federal states. However, that alone does not solve the problem of inferior quality of mineral waste, even after treatment, compared to natural materials. This is also the reason why different quality levels have been defined for recycling aggregates, soil-like materials, and incineration bottom ashes in the decree. The best quality levels can often only be achieved with sub-fractions of materials.

Whereas the coarse fraction of **C&D waste** (>2 mm) can usually be used as an aggregate without limitations, the utilization of the sand fraction is problematic due to higher contaminant contents. The manual sorting of the coarse fraction (>16 mm) of treated C&D waste revealed that the best exploitable fraction "stones" had a contamination amount of only 14.2%. The 25.8%-share of bricks leads to the lower classification of recycled aggregate type 2 (brick content <30%), according to DAfStb [27]. The treatment was performed with a mobile jigging machine [24]. With further optimization, the separation of the brick fraction from the stone and mortar fraction seems applicable since the difference in density between brick and concrete is high enough (bulk density 1.63 g cm^{-3} versus 2.42 g cm^{-1}, [37]).

For the utilization of **soil-like materials**, requirements of various legal areas must be considered, the aim of which is to promote the circular economy for the conservation of natural resources and, at the same time, to ensure precautions against harmful soil changes. The utilization of soil-like material looks promising since it has been accepted that the release of contaminants such as PAHs is more relevant than the mere content in the solid. However, complex contamination with organic and inorganic pollutants may present a barrier to more widespread utilization. The utilization of soil-like materials with low PAH-release can still fail when certain limits for heavy metal leaching or sulfate are exceeded. Overall, it has been shown that the new requirements of the amended

German Federal Soil Protection and Contaminated Sites Decree [21] are appropriate to open additional possibilities for the high-quality utilization of soil-like materials, e.g., for backfilling, recultivation, renaturation, composting, or landscaping.

Most **incineration bottom ash** in Europe undergoes a treatment process, at least for the separation of iron and other metals. The average energy demand for the treatment is 29.8 MJ/ton. However, among 17.65 million metric tons in the year 2018, around 50% ended up as unrecovered material in landfills, along with a considerable amount of elemental metals [38]. The recovery of elemental metals, such as Fe, Al, and Cu (and the respective alloys) from IBA exhibit the most prominent advantage in the management of this waste [19]. The utilization of the elemental metals in metallurgy leads to approximately 62.5 kg CO_2-eq. per ton of incinerated waste, indicating the global warming potential of the waste incineration process [39]. For comparison, the incineration of municipal solid waste has an impact of approx. 850 kg CO_2-eq. per ton of waste incinerated. The mineral part of IBA, i.e., the majority (with 90%), is more problematic regarding utilization. Only the smaller part of IBA is disposed of in landfills. Utilization takes place in technical structures, road construction, and in landscaping work (also in landfills) [40]. For these applications, IBA is in competition with recycled aggregates from C&D waste. However, the pollutant and impurity level of IBA is higher. The significantly higher chloride content in IBA precludes its application in concrete production. However, during the storage of IBA and even when landfilled, the relatively high concentration of alkaline substances such as CaO yields the favorable effect of sequestering CO_2 from the atmosphere.

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