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Comparison of different post-demolition autoclaved aerated concrete (AAC) recycling options

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Abstract. Autoclaved aerated concrete (AAC) is used as masonry blocks and prefabricated reinforced elements preferably in residential buildings. Due to its porous structure and mineral composition, it combines low thermal conductivity and fire resistance properties. Consequently, the popularity of AAC increases. However, due to significant AAC production volumes in many European countries since the 1960s and 1970s and given building lifetimes, strongly increasing post-demolition AAC waste volumes can be expected in the following decades. Recycling these post-demolition AAC wastes could protect primary resources and landfill capacities and reduce greenhouse gas emissions. But, recycling of post-demolition AAC is not yet established. The majority of the waste is landfilled even though landfill capacities have decreased and the legal framework conditions in Europe regarding a circular economy are becoming stricter. Therefore, new recycling options are needed. Current research approaches propose different open-loop recycling routes for post-demolition AAC, e.g. lightweight aggregate concrete, lightweight mortar, no-fines concrete, floor screed, animal bedding, oil- and chemical binders, and insulating fills for voids and interstitial spaces. Additionally, closed-loop recycling is possible and under research. Finely ground post-demolition AAC powder can be directly used in AAC production or can be chemically converted to belite (C2S) clinker to substitute primary cement in AAC production. These promising recycling options are compared regarding environmental and economic aspects. We find that the resource consumption is lower in all recycling options since post-demolition AAC helps to save primary resources. Furthermore, greenhouse gas emissions associated with the substituted primary resources are saved - especially when substituting primary cement in closed-loop recycling. In economic terms, increasing landfill costs could be avoided, which leaves a considerable margin for the cost of pre-processing, transport and recycling. The results can help decision-makers to implement circular management for AAC by fostering post-demolition AAC recycling and reducing its landfilling.

Keywords: Autoclaved aerated concrete, post-demolition recycling options, assessment, closed-loop

1. Introduction

Building construction, operation, and demolition are associated with large material flows, energy consumption, and greenhouse gas (GHG) emissions. Many options exist to reduce energy and GHG efforts, including autoclaved aerated concrete (AAC). AAC is a popular construction material, especially for residential buildings. Its key characteristic is countless tiny pores formed by hydrogen from a chemical reaction of aluminium with the alkaline suspension consisting of sand, cement, quicklime, anhydrite, and water. Consequently, AAC has a low density reaching 300 kg/m^3 and less while the compressive strength is sufficient to build one- or two-family houses. Thus, the main advantages of AAC are its excellent thermal insulation property, high fire resistance, and a fast and low-cost construction process due to large AAC masonry blocks and no need for further insulation. In 2018, the global production capacity for non-reinforced AAC blocks summed up to 450 million m^3 [1], while the current annual European AAC production exceeds 16 million m^3 [2]. Russian AAC production equaled 11.6 million m^3 in 2017 [3].

Nowadays, a rising amount of post-demolition AAC (pd-AAC) from the building stock is expected to emerge. [4] estimate a volume of 1.3 million m^3 for Germany in 2021 which could increase to more than 4 million m^3 in the following decades. Currently, the pd-AAC is collected jointly with other gypsum-containing demolition wastes. Thus, it is usually not recycled but landfilled. But demolition waste recycling is essential to preserve natural deposits of primary resources, reduce GHG emissions, and fulfil legal requirements like the European waste and recycling regulation [5] that stipulates recycling rates of 70% for demolition wastes. Additionally, landfill capacities are limited, and landfill fees are expected to rise [6, 7]. Besides environmental advantages, increasing landfill fees are an economic incentive for more complex and cost-intensive recycling processes.

Therefore, developing additional recycling options for pd-AAC is crucial. Demolition wastes, in general, are often recycled in road construction, earthworks, civil engineering, concrete production, and landscaping [7]. However, for pd-AAC, its porous structure, low compressive strength, and sulphate content eliminate those possibilities. The current research analyses and suggests new pd-AAC recycling options. However, the pd-AAC quality differs strongly due to various impurities, e.g., timber, glass, metal, ceramics, wallpaper, and gypsum that may adhere to pd-AAC. Chemical recycling options are necessary that can handle those impurities, insofar as their separation by mechanical treatment and sorting is not possible. In particular, the production of RC cement clinker based on the mineral belite allows recycling of low-quality pd-ACC fines and, if necessary, the separation or chemical fixation of pollutants.

2. State-of-the-art recycling technology and pd-AAC recycling options in the literature

AAC is mainly produced in the form of masonry blocks which generally also persist during demolition. However, reuse of whole AAC blocks is not practical since this would require a careful deconstruction without any breakage at the edges, cleaning, transport, and storage. Instead, pd-AAC is pre-processed for different recycling options. The pre-processing consists of crushing, grading, and purifying [8]. In the crushing process, pd-AAC is processed to coarse-grained pd-AAC granulate with a grain size between 15 and 1 mm. As an unwanted by-product, fine pd-AAC powder (0/1 mm) occurs with a very unfavourable approximate mass distribution of up to 75% powder and 25% granulate. Since AAC is a relatively soft material compared to concrete or clay bricks, state-of-the-art rock crushing machinery is usable. A grading process follows the crushing to separate the powder from granulate. These two outputs have different characteristics. The pd-AAC powder resembles sand due to its fine grains, while the pd-AAC granulate forms pebbles that keep the porous AAC structure. Therefore, different recycling routes for powder and granulate are necessary. A final purifying process is performed for both materials to improve the quality of the recycling material and remove impurities like wood, plaster, wallpaper, metals/screws, dowels, and ceramics. Generally, impurities sum up to a low one-digit mass percentage (expert interview).

Current research investigates new, high-quality recycling options for pd-AAC powder and granulate. Among these options, closed-loop recycling and open-loop recycling has to be differentiated. Closed-loop recycling means to recycle a secondary raw material in the same product, e.g., the use of pd-ACC in primary AAC production. Open-loop recycling includes all other options, sometimes also referred to as cascade use/recycling. Closed-loop recycling is desirable since a theoretically infinite circularity of material use could be established, and high-quality recycling is guaranteed. [9] describes the pd-AAC powder recycling in AAC production. Up to 20% of the primary raw materials (mainly sand, cement, and quicklime) can be substituted by pd-AAC powder (alternative 1). [10] describe the substitution of up to 50% of the primary sand by pd-AAC powder in AAC production (alternative 2). Pd-AAC powder could also be used to produce belite cement clinker as shown by [11]. In this process, pd-ACC powder replaces limestone, with an estimated lower limit of 35% reduction of GHG emissions compared to ordinary Portland cement (OPC) clinker (Stemmermann et. al., in. prep.). The partial substitution of up to 50% of Portland cement by belite cement clinker in AAC production has been successfully tested in first laboratory trials. Other applications are investigated. This recycling option is particularly suitable for the production of high-quality products from low-grade and slightly contaminated residues as valuable and associated harmful substances can be separated or fixed in insoluble minerals. Furthermore, the overall energy consumption could be reduced.

Besides, many open-loop recycling options for pd-AAC powder and granulate are investigated and discussed in literature. On the one hand, recycling of pd-AAC granulate outside the construction sector is proposed. These options include animal bedding and granulates for technical applications (i. e. oil and chemical binders), two reutilization options already used today for AAC production remains and job site leftovers. Further proposed options are the bioactivation for methane emission reduction in landfills [12], the use as filter material for phosphorus wastewater [13], soil conditioner and fertilisers [14, 15], and construction of ponds, canal bases, and embankments [16]. On the other hand, open-loop recycling of pd-AAC powder and granulate in the construction sector is investigated. Pd-AAC powder recycling options focus on the substitution of sand or the use of the powder as filler. Applications suggested in the literature include the use in cement clinker production [17][1], in concrete production [18], and in light mortar production [19]. In contrast, pd-AAC granulate recycling focuses on the porous structure of the granulate. The granulate could be used for shuttering block production from no-fines concrete (concrete without fine aggregates like sand) [18] and lightweight aggregate concrete (LWAC) production [18, 19]. Finally, a mixture of pd-AAC powder and granulate could be recycled in floor screed [20]. All references indicate that the pd-AAC quality is high enough to achieve good technical properties of the respective final products.

3. Comparison methodology of different recycling options

In this study, the pd-AAC recycling options are compared with each other and with landfilling, which is the current standard to handle pd-AAC. The processes under consideration besides the landfilling are the pre-processing (crushing, grading, purifying), transportation processes, and the use of the pd-AAC powder and granulate to substitute primary raw materials. Previous life cycle stages of the pd-AAC, like the production and use phase, are not included in the comparison following the so-called zero burden approach [21]. The idea of this approach is that efforts for the previous stages would be the same for all compared end-of-life options and would thus not influence the results of the comparison. The focus of the comparison is on environmental and economic aspects. Environmental aspects include landfill capacity [m^3], resource consumption [tons], and GHG emissions [kg CO2-Eq], respectively climate change potential of the end-of-life processes, transportation processes, and potential savings by substituting primary raw materials. Data for these considerations are taken from the ecoinvent 3.8 dataset. Economic aspects include transportation and landfilling costs.

[1] This study concludes that pd-AAC recycling in cement clinker production is possible but no practical. Therefore, this option will not be further investigated.

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4. Results

First, environmental aspects of pd-AAC recycling are investigated. Fostering pd-AAC recycling would significantly reduce the landfill capacity used for pd-AAC. Today, pd-AAC is disposed in landfills (56%) and low-grade utilisation (34%) especially in backfilling. This sums up to around 90% of all treatment options [22, 23]. In contrast, only small amounts of impurities are sorted out from the pd-AAC in a purifying process before it is recycled and potentially has to be landfilled. Thus, landfilling could nearly completely be replaced by pd-AAC recycling. For Germany alone, this results in around 0.73 million m^3 landfilled pd-AAC which equals 56% of the 1.3 million m^3 of pd-AAC in 2021 [4]. Until 2050, this is predicted to exceed 2.3 million m^3 pd-AAC [4]. Another 0.44 million m^3 (34%) pd-AAC that is expected to be fed to low-grade utilisation in 2021 (1.4 million m^3 in 2050) also could be used for high-quality recycling. Besides saving limited landfill capacity, high-quality recycling could also reduce primary energy and raw material consumption.

Proposed recycling options for pd-AAC powder and granulate in the building sector usually substitute basic materials like sand (e.g. floor screed) or cement (e.g. AAC), as well as lightweight aggregates like expanded clay (e.g. LWAC) by pd-AAC material. Production recipes given in the literature suggest that the amount of pd-AAC approximately equals the amount of substituted primary material. Therefore, the resource consumption of sand, cement, lightweight aggregates, and other basic materials can be reduced using the 0.73 million m^3 pd-AAC from landfilling and 0.44 million m^3 from low-grade utilisation in 2021. This sums up to 1.17 million m^3 pd-AAC for high-quality recycling in 2021 and estimated 3.7 million m^3 in 2050. This amount equals around 0.6 million tons in 2021 and up to 1.75 million tons until 2050, assuming a rather high pd-AAC density of 0.5 t/m^3. **Fehler! Verweisquelle konnte nicht gefunden werden.** shows potential substitution amounts of primary raw materials by pd-AAC in the AAC, light mortar, shuttering block, LWAC, and floor screed production based on the above-mentioned references (see Table 1).

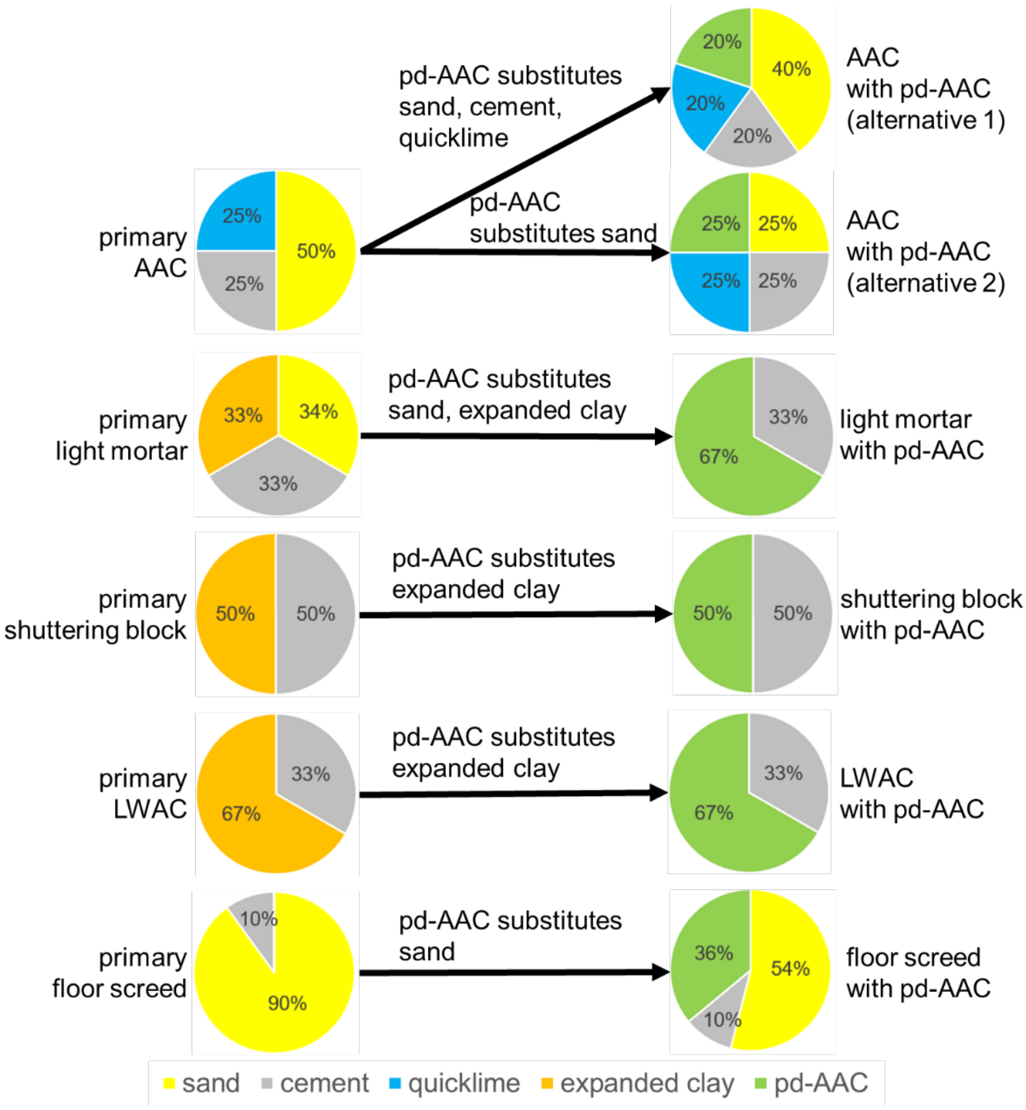

Figure 1. Input share of different resources in primary production and pd-AAC share (green) in AAC, light mortar, shuttering block, LWAC, and floor screed with pd-AAC recycling content.

Besides, this substitution of primary materials comes along with savings of GHG emissions. The ecoinvent 3.8. dataset (2021) gives climate change potentials[2] of 0.875 kg CO_2-Eq/kg for cement, 1.15 kg CO_2-Eq/kg for quicklime, 0.012 kg CO_2-Eq/kg for sand, and 0.401 kg CO_2-Eq/kg for expanded clay. Therefore, substituting cement or quicklime with pd-AAC is associated with a significant GHG emission reduction. Using the pd-AAC granulate as lightweight aggregates to substitute expanded clay would also reduce emissions from primary production. However, primary sand is associated with low GHG emissions, so a substitution of sand would not reduce GHG emissions considerably. In the following, we show the results of a rough estimation of GHG mitigation potentials for different end-of-life scenarios of pd-AAC. Table 1 summarizes information on resources needed for primary production, substituted primary material, and substitution percentage. Furthermore, overall potential GHG savings for all recycling options for pd-AAC mentioned above are calculated. Table 2 shows how the overall

[2] IPCC 2013 methodology, GWP 100a.

potential GHG savings are composed of regarding their substitution of sand, cement, quicklime or expanded clay respectively. These savings are calculated by multiplying the above-mentioned CO_2 factors from ecoinvent 3.8 with the respective substitution amount (input share of sand/cement/quicklime/expanded clay multiplied by overall substitution percentage). The GHG savings cannot be calculated for the recycling options outside the construction sector since these are new application fields without the possibility of quantification of the substitution of primary materials. For the other recycling options, the savings are considerably higher when cement, quicklime, or expanded clay are substituted compared to those recycling options where pd-AAC is used for sand substitution. Overall, the recycling options "shuttering block" and "LWAC" show the highest potential GHG savings per kg product, partly because the share of primary inputs substituted by pd-AAC is higher than in other end-of-life options e.g. in the AAC production.

Table 1. Potential GHG savings in different pd-AAC recycling options.

Recycling option	Substituted primary material	Substitution percentage	Overall potential GHG savings [kg CO_2-Eq per kg product]	Reference	Assumed primary production recipe
AAC (alternative 1)	Sand, cement, quicklime	20%	0.102	[9]	50% sand, 25% cement, and 25% quicklime
AAC (alternative 2)	Sand	50%	0.003	[10]	see alternative 1
Concrete	- (filler material)	-	-	[18]	-
Light mortar	Sand, expanded clay	100%	0.138	[19]	33.3% cement, 33.3% sand, and 33.3% expanded clay
Shuttering block from no-fines concrete	Expanded clay	100%	0.201	[18]	50% cement, and 50% expanded clay
LWAC	Expanded clay	100%	0.267	[18, 19]	33.3% cement and 66.6% expanded clay (average of different production recipes in literature)
Floor screed	Sand	40%	0.004	[20]	10% cement, and 90% sand

Table 2. Composition of the potential GHG savings in different pd-AAC recycling options given per substituted material.

Recycling option	Potential GHG savings [kg CO_2-Eq per kg product] through sand substitution	Potential GHG savings [kg CO_2-Eq per kg product] through cement substitution	Potential GHG savings [kg CO_2-Eq per kg product] through quicklime substitution	Potential GHG savings [kg CO_2-Eq per kg product] through expanded clay substitution	Overall potential GHG savings [kg CO_2-Eq per kg product]
AAC (alternative 1)	0.001	0.044	0.058	0	0.102
AAC (alternative 2)	0.003	0	0	0	0.003
Concrete	-	-	-	-	-
Light mortar	0.004	0	0	0.134	0.138
Shuttering block from no-fines concrete	0	0	0	0.201	0.201
LWAC	0	0	0	0.267	0.267
Floor screed	0.004	0	0	0	0.004

To reach the above-calculated savings, the pd-AAC has to be pre-processed (crushed, graded, and purified) and transported before being processed in the respective end-of-life option. Efforts for these pre-processes and transportation reduce the savings. However, ecoinvent 3.8 indicates that the crushing only causes GHG emissions of 0.0003 kg CO2-Eq/kg input, the grading and purifying combined[3] leads to 0.008 kg CO2-Eq/kg input, and transportation[4] results in 0.087 kg CO2-Eq/t×km. Thus, the total GHG emissions for pre-processing of pd-AAC sum up to only 0.017 kg CO2-Eq/kg input, assuming a transport distance of 100 km. Therefore, all recycling options where cement, quicklime, or expanded clay are substituted are beneficial from an environmental point of view.

Besides environmental aspects, a preliminary economic consideration is performed. For this purpose, landfilling costs are compared to transport costs to recycling sites and pre-processing costs to evaluate how high the margin for recycling is. For Germany, the pd-AAC landfilling costs including transport and provision of a container sum up to an average of 190 €/t.[5] If an alternative end-of-life option prevents these landfilling costs, they can be considered as the available budget for pre-processing, recycling and transport. Additionally, if the purified pd-AAC powder and granulate are sold to producers the earnings further increase this budget. Furthermore, landfilling costs will continue to rise due to decreasing landfill capacity, and rising CO_2 taxes can be expected in the future which will increase the price of CO_2-intensive primary materials like cement and of transport. The pre-processing steps needed for high-quality pd-AAC are state-of-the-art, and machinery/procedures are already widely used for other mineral materials today. So, no additional investments are required for the pre-processing steps. The NIR sorting of mineral construction and demolition waste which would be an essential part of the purifying process costs up to 1.50 €/t [24]. And, average transport costs sum up to around 20 €/t for a transport distance of 100 km or 28 €/t for a transport distance of 200 km [25]. Thus, overall pd-AAC recycling seems to have economic potential.

[3] The process „treatment of waste brick, sorting plant" is used for a combined grading and purifying, because there is no matching process for grading in the database and the treatment usually combines sorting/purifying and grading. Waste brick is comparable to pd-AAC as both are mineral masonry materials, however with slightly differing material densities.

[4] Pd-AAC is assumed to be transported in a lorry with more than 32 metric tons with EURO6 standard.

[5] These cost data were obtained by searching the online portals abfallscout.de and clearago.de.

5. Discussion

This study compares recycling options for pd-AAC based on environmental and economic indicators. However, no complete life cycle assessment is performed considering all inputs, outputs and various impact categories. Such a life cycle assessment would directly compare the recycling options based on a defined functional unit within defined system boundaries. In a simplification, this study roughly calculates CO2 savings per kg product compared to the current pd-AAC end-of-life option. This is less effortful than full LCAs, but reduces comparability between the considered end-of-life options as pd-AAC percentages in the products vary significantly between the different recycling routes. And, this simplified study excludes additives as well as carbonation during use or landfilling. In the preliminary economic analysis, only standard transport distances of 100 km and 200 km are considered. However, real transport distances might vary. Additionally, for both the environmental and economic assessment, a precise examination of transport distances/costs based on a location and logistics planning for the recycling network would be necessary to confirm the findings under realistic conditions.

6. Conclusion

Among the possible recycling options for pd-AAC presented in literature, those substituting primary cement, quicklime, or expanded clay in construction materials are the most advantageous concerning mitigation of GHG emissions. Within our estimations, the highest savings can be reached by pd-AAC recycling in LWAC (0.267 kg CO2-Eq per kg product). Overall, pd-AAC recycling could avoid landfill capacity of around 0.73 million m^3 in 2021 and up to 2.3 million m^3 in 2050 in Germany. Furthermore, pd-AAC recycling could reduce primary resource consumption by about 0.6 million t in 2021 and about 1.8 million t in 2050 in Germany. Besides, landfilling costs for pd-AAC in Germany are likely to be higher than average transport and pre-processing costs which already provides an economic incentive for recycling. Future research should further investigate the economic and environmental impacts of the pd-AAC recycling in depth by conducting a full LCA and gathering field data for pre-processing, recycling, and transportation costs and associated environmental efforts. These analyses are currently being worked on by the authors.

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