

Manufacturing and Application of Lightweight Aggregates from Construction and Demolition Waste

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The objective of the REALight project is the development of a thermal process to produce lightweight aggregates in pilot scale and the implantation of a method to recover gypsum. Beside construction and demolition waste, various industrial by-products are studied as raw materials. The raw materials have so far been unused or used in applications with lower quality requirements. To prove the performance of the lightweight aggregates, their technical properties are tested and their use in different applications is studied, e.g., for lightweight mortars as well as lightweight concretes.

Keywords: Construction/demolition waste, Flue gas desulfurization gypsum, Industrial by-products, Infra-lightweight concrete, Lightweight aggregates

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1 Introduction

In Germany, more than 60 million tons of construction and demolition waste (CDW) consisting of concrete and masonry rubble are produced annually [1]. The recyclability of mixed masonry rubble is severely limited because it is a mixture of different wall-building materials such as bricks of various qualities, sand-lime bricks, lightweight concrete, and aerated concrete as well as mortar and plaster. The different physical properties of the individual building materials, such as porosity and strength, frost resistance, and impurities like sulfate-containing components, are the main reason for the poor recyclability. Therefore, their use is limited to applications with low quality requirements, such as backfilling of shafts and pits at construction sites or construction measures and profiling at landfills. In the case of high sulfate contents, the use may even be inadmissible for these applications for reasons of groundwater protection. To avoid low-quality applications, completely new ways of processing and recycling of building materials must be adopted.

German coal-fired power plants produce more than 6 million tons of flue gas desulfurization (FGD) gypsum per year. Almost all is used as a raw material in gypsum and cement industries and 60 % of the gypsum demand is covered by FGD gypsum [2]. With the environmentally necessary phase-out of coal-fired power generation, this valuable secondary raw material will disappear. Alternative sources must be found and developed. The challenge of

domestic primary raw materials shortage and FGD gypsum lack are confirmed in recent publications, e.g., by the Federal Institute for Geosciences and Natural Resources (BGR) and the German Environment Agency (UBA) [3, 4].

The future demand of the building industry for lightweight aggregates (LWA) and gypsum will probably not decline because the lightweight materials form one basis for sustainable constructions [5]. Against this background, the REALight research project is of great economic relevance.

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2 Construction and Demolition Waste and Other Secondary Raw Materials for the Production of Lightweight Aggregates

Laboratory-scale studies for the application of brick-containing CDW to produce lightweight aggregates were carried out as part of the research project “AufbauKörnungen”. This project was founded by the German Federal Ministry of Education and Research within the framework of the “r2 – Innovative Technology for Resource Efficiency – Resource Intensive Production Processes” funding priority. The results show that material that was considered to be appropriate for low-value recycling can be processed into a high-value product if the appropriate technology is available. An advantage of the novel LWA manufactured from CDW is that the process requires almost no primary resources [6–8].

Industrial by-products are also a source of raw materials for the production of lightweight aggregates. Well-known examples include coal fly ash and bottom ash from power plants, which can directly be used as aggregates following mechanical processing. Recovered glass is often employed as raw material, too [9]. Further industrial residues under consideration for the manufacture of LWA are described in literature, such as coal wash waste and flotation residues from coal processing [10], ash from combustion processes [11], fine particle waste from pumice processing [12] or sediments and sludge from rivers, lakes, and water reservoirs as well as sewage sludge [13].

3 The R&D Project REALight

3.1 Objective

The focus of REALight is the further development of a process to produce lightweight aggregates together with the implantation of a method to recover gypsum and with tests to use industrial by-products as input materials [14, 15]. For this purpose, the mineral waste is converted to lightweight aggregates in a thermal process. This process is a typical feedstock recycling by a chemical and mineralogical conversion. CDW containing bricks is milled, mixed with the bloating agent silicon carbide (SiC), granulated, and burned in a rotary kiln to produce the LWA. Sulfates present in the construction waste are decomposed and subsequently separated by means of a flue gas scrubber. They can substitute conventional FGD gypsum. The joint research project contains the following focal points:

- Raw material assessment to expand the raw material base beyond construction and demolition waste including necessary pretreatment and preparation.
- Development of the production process for lightweight aggregates from CDW in a pilot plant.
- Sulfate removal from gypsum-containing input materials and production of FGD gypsum.

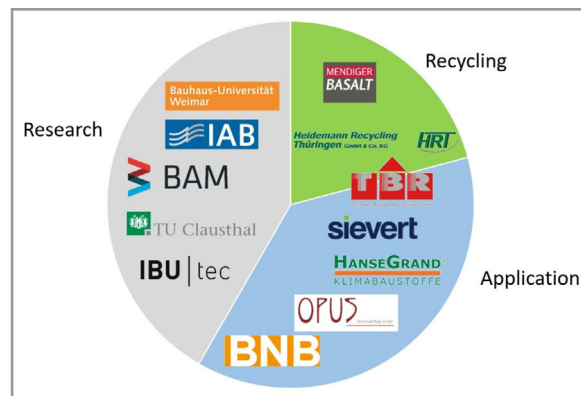


Figure 1. Consortium and tasks in REALight.

- Comprehensive characterization of the lightweight aggregates according to European standards.
- Application of the lightweight aggregates in lightweight concretes, lightweight repair mortars for monument conservation, and dry mortar mixtures as well as unbound systems in garden and landscape constructions and green roof systems.

3.2 Project Network Structure and Tasks

In REALight, twelve partners from different fields of building material production and application, waste treatment, process engineering as well as research and development are involved. Fig. 1 provides an overview of the project partners and their main tasks.

The involvement of several small and medium-sized German enterprises contributes directly to demonstrate the innovative power of the project in terms of economic viability, utilization, and suitability of the products for marketable applications. At the same time, the companies specify the requirements for the lightweight aggregates' properties, which have to be adjusted. Beside the research partners and different recycling specialists, four companies representing the various applications are involved.

In all areas of application, there is pressure to replace natural lightweight aggregates, such as pumice and other volcanic rocks, and lightweight aggregates produced from natural raw materials, such as expanded clay, slate, perlite with regard to a more sustainable production. Quarries for natural lightweight aggregates and clayey materials will running out of raw materials with desired characteristics. Lightweight aggregates based on secondary raw materials are practically not available on the market. One exception is expanded glass, but it is not suitable for all applications.

This publication focuses on the results of raw material assessment, LWA production, and LWA application in lightweight and infra-lightweight concretes (ILC) as well as in stone repair mortars.

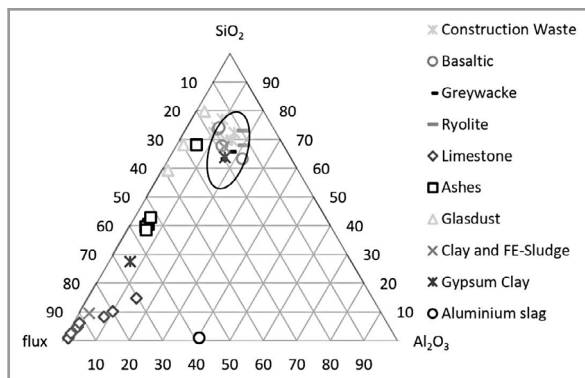


Figure 2. Classification of residual and waste materials in the ternary diagram SiO_2 - Al_2O_3 -flux.

4 Raw Material Assessment

Previously unused or low-level reused mineral construction waste, such as mixed masonry rubble, is employed as raw material. To broaden the raw material base, the suitability of other mineral wastes as raw material or bloating agent is investigated in a raw material assessment, overseen by Technische Universität Clausthal. The assessment of the suitability of a raw material to produce lightweight aggregates is made on the basis of Riley's investigations in the bloating behavior of clays [16]. Therefore, the results are presented within a ternary diagram (Fig. 2) of the main mass fractions of the oxides SiO_2 , Al_2O_3 , and flux. The diagram is extended by a zone of optimal bloating properties. As part of the research, more than 35 residual and waste materials in a variety of grain fractions are examined for their potential suitability to produce lightweight aggregates [17].

Based on the results of the chemical analysis the most promising substances are classified as basically suitable for further investigations. In addition to fine brick materials, crushed sands and dusts of graywacke, tuff, rhyolite, quicklime, and dolomite as well as a ferruginous sludge are included in the studies. Studies on the bloating behavior using a heating microscope are also performed at IAB Weimar gGmbH. To compare the results, similar tests with the use of a muffle oven are conducted at Technische Universität Clausthal. Thereby graywacke and rhyolite are showing good bloating properties. This confirms the expectations about the suitability of magmatic rocks for the production of LWA without or with a lesser amount of bloating agents such as silicon carbide.

Mixtures with various concentrations of additives, such as Fe slurry, led to higher proportions of flux. This had no or only a slight influence on the bloating properties. The downside of higher flux concentrations is the earlier melting of the aggregates. However, this goes hand in hand with the possibility to reduce the firing temperature. Further investigations are needed to evaluate whether this could be a promising approach toward energy and cost savings.

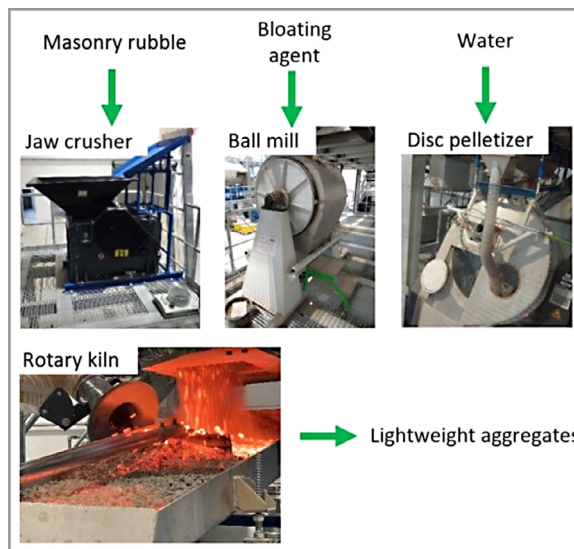


Figure 3. Process scheme of the production of lightweight aggregates.

The suitability of other residual materials, such as electric furnace slag, converter slags, and slags from waste incineration, is currently under examination. At the time of publication, it can be said that none of the examined slags showed promising bloating properties. Further ongoing research is carried out to identify economically favorable bloating agents as substitutes for SiC powder. To date, no bloating agent is identified, which can serve as a substitute for high-cost SiC available on the market in sufficient quantities. Studies on the suitability of recycled SiC materials, graywacke and two different SiC-free compounds as bloating agents are currently ongoing. Especially the studies on the use of the compounds without SiC are promising, but not yet finished.

5 Manufacturing of Lightweight Aggregates in Pilot Scale

In the pilot plant of IAB Weimar gGmbH, a jaw crusher, a batch ball mill, and a granulating plate (Fig. 2) are used for the preparation of the masonry rubble used as raw material. First, the material is crushed to particle sizes < 10 mm using a jaw crusher without further material drying or pre-treatment. Then, the material is ground in a ball mill under addition of the bloating agent to particle sizes < 100 μm . Afterwards, the material powder is granulated. The produced "green granules" are finally stabilized and expanded in a thermal process using a rotary kiln (Fig. 3).

The rotary kiln has a length of 6 m and a clear diameter of 0.6 m. The speed and inclination of the kiln are adjustable. The kiln is fired with natural gas. For the lightweight aggregate production, the kiln operates at a firing temperature of 1200 °C. The total residence time of the granules in the kiln

is approx. 25 min. Of these, the material is exposed to the required sintering temperature of over 1100 °C for approx. 6 min. This period is not sufficient to exploit the full bloating potential. For this reason, the granules were subjected to the thermal treatment a second and in some cases a third time [18].

Several test campaigns to produce lightweight aggregates were carried out in the pilot plant of IAB Weimar gGmbH. So far, 2.4 t of lightweight aggregates of different grain sizes has been produced in the pilot plant. Thereby, different types of CDW containing brick were tested to produce the novel LWA. More details about the production process, raw materials used, and characteristics of LWA are already described in previous publications [16]. The lightweight aggregates were used for comprehensive material characterization and application tests with the project partners of REALight.

Furthermore, sulfate separation by thermal decomposition forms the basis to produce FGD gypsum. The basic feasibility of sulfate separation in the firing process was confirmed. Although thermal dissociation of pure anhydrite occurs only above 1200 °C, in the presence of foreign oxides, as present in CDW, decomposition of sulfate shifts to lower temperatures. Differential scanning analyses confirmed this shift. Up to a gypsum addition of 15 % by mass, complete decomposition was achieved at temperatures below 1200 °C [19, 20]. By means of a gas scrubber and a stationary gas analysis system, FGD gypsum is recovered from the flue gas. Anyway, further studies have to be carried out to bring the FDG gypsum recovery to full technical functionality.

6 Application of Lightweight Aggregates

In REALight, the LWA are tested in different applications, such as lightweight and infra-lightweight concrete as well as in repair mortars for the preservation of monuments.

6.1 Application of Lightweight Aggregates in Lightweight Concrete Hollow Blocks

Lightweight concrete blocks are widely used in masonry constructions. Pumice or expanded clay are usually employed as lightweight aggregates in the production of these blocs. At least in the case of pumice, the shortage of raw materials is clearly becoming apparent. Whether the lightweight aggregates from masonry rubble can be an alternative is investigated in operational tests at a lightweight concrete manufacturer. The starting material for the six

Table 1. Initial mixtures of the operational tests and parameters of the blocks produced.

Component	Mix Nr. 6_1	Mix Nr. 6_2	Mix Nr. 7_1	Mix Nr. 7_2
Pumice sand [kg]	72.7	72.7	70.3	70.3
Leca 2–4 mm	41.2	41.2	0	39.8
LWA from masonry rubble ^{a)} 2–4 mm	0	0	39.8	0
LWA from masonry rubble ^{a)} 4–8 mm	82.3	82.3	39.8	76.6
LWA from masonry rubble ^{a)} 8–12 mm	48	82.3	79.6	76.6
Liapor 6/12	34	0	0	0
Cement	100	100	75	75
Water [L]	11	12	9	10
Water/cement ratio	0.11	0.12	0.12	0.13
Apparent density [kg dm ⁻³]	0.86	0.77	0.64	0.68
Compressive strength [N mm ⁻²]	4.1	4.7	2.7	2.7
Thermal conductivity at 10 °C [W(m K) ⁻¹]	0.268	0.269	0.203	0.220

a) Manufactured by thermal process.

tests were lightweight aggregates of masonry rubble and, in addition, a pumice sand as well as the commercial products LECA and Liapor (Tab. 1). The proportion of aggregates of interest here was 0.47 to 0.69 kg aggregate per kg total aggregate. A cement CEM II/B-P 42.5 N was used.

No irregularities are observed in the production of any of the mixtures tested. The parameters measured on the manufactured bricks achieve the requirements of the general building approval for lightweight concrete blocks.

6.2 Application in Infra-Lightweight Concrete

The novel LWA made from masonry rubble was used to produce ILC. ILC refers to lightweight concrete with a dry bulk density of ≤ 800 kg m⁻³. Due to its favorable structural-physical properties, ILC can be used for monolithic and simple construction without complicated connections and details. Load-bearing exterior walls made from ILC do not require additional thermal insulation. The concrete formulation for the ILC within the REALight project was developed by Beton und Naturstein Babelsberg GmbH and was adjusted by Bundesanstalt für Materialforschung und -prüfung (BAM). About 65 vol.-% of the total aggregate volume consisted of the LWA 2–4 mm and LWA 4–8 mm. Expanded glass was used for the fine aggregates with grain sizes ≤ 2 mm. The low-CO₂ binder Celitement was employed instead of conventional cement [22]. The composition of the concrete is given in Tab. 2, and the physical and mechanical properties of the ILC at the age of 28 days are summarized in Tab. 3.

The obtained concrete can be classified as ILC because of its dry bulk density of 800 kg m⁻³. According to the definition of for ILC, the concrete can be assigned to the compressive strength class ILC 7 [24]. Furthermore, the concrete shows minor shrinkage and has a very good frost-thaw resistance. Overall, the ILC containing the novel aggregates

Table 2. Composition of fresh infra-lightweight concrete [21].

Component	Amount [kg m ⁻³]
Binder Celiment	373
Water	171
Silica	73
PCE superplasticizer	10
Shrinkage reducing admixture	2
Liaver 0.5–1 mm	64
Liaver 1–2 mm	50
LWA from masonry rubble ^{a)} 2–4 mm	177
LWA from masonry rubble ^{a)} 4–8 mm	215

a) Manufactured by thermal process.

Table 3. Characteristic properties of the infra-lightweight concrete at the age of 28 days and 28 freeze thaw cycles (FTC), respectively [22, 23].

Property	Quantity
Compressive strength cube 150 mm [MPa]	10.8
Compressive strength cylinder 100 mm [MPa]	8.7
Flexural strength [MPa]	1.4
Dry bulk density [kg m ⁻³]	800
Skeletal density [kg m ⁻³]	2200
Total porosity [%]	63.5
Static E-modulus [MPa]	4200
Shrinkage [mm m ⁻¹]	-0.43
FTC scaling [g m ⁻²]	77

manufactured masonry rubble shows comparable physical and mechanical properties to other ILC with similar bulk densities containing CEM II as binder and expanded clay as LWA [25, 26].

Finally, ILC facade elements with the dimensions of 125 cm × 60 cm × 10 cm are produced by Beton und Naturstein Babelsberg GmbH (Fig. 4). In this way, it has been demonstrated that the LWA developed in the REALight project are suitable for the use in concrete. The LWA produced from mineral CDW are a good alternative to currently employed expanded clays.

6.3 Application in Lime-Based Repair Mortars for Sandstone Conservation

Lightweight mortars are preferred for sandstone conservation due to

their relatively low weight. Especially for the conservation of overhanging parts, the total weight of the mortar is crucial. Lime-based mortars are traditionally used for sandstone conservation, as the chemical, physical, and mechanical properties of the mortar match very well with those of the sandstone. Opus Denkmalpflege GmbH and Bundesanstalt für Materialforschung und -prüfung (BAM) developed a two-layer mortar system, which consists of a filling and a covering mortar for conservation of Cotta sandstone. The filling mortar is used to fill large voids, while the covering mortar is taken to modulate the surface texture to the damaged stone. Both mortars contain fine crushed grains of the novel LWA produced from masonry rubble.

The compositions of the dry mortar mixtures are given in Tab. 4. The mixtures were mixed with water in a rotating pan mixer (Zyklus Pemat) for no longer than 7 min in total. The fresh mortar was transferred into prismatic moulds (160 mm × 40 mm × 40 mm). The moulds were stored at 23 °C and 65 % relative humidity. The prisms were demoulded after seven days and stored under the same climate conditions before testing.

The repair mortar must be the weakest part of the mortar-sandstone system. If the repair mortar is lost or damaged, the system should fail either in the mortar itself or at the interface to the stone but never in the restored stone. Therefore, it is recommended that the compressive strength of the mortar should be less than 60 % of the compressive strength of the damaged stone [28]. For the conservation of Cotta sandstone, the ideal cement-free mortar should be a M 2.5 mortar and the ideal cement mortar M 5. Both requirements are achieved by the two mortar formulations containing the crushed fine LWA. The development of the compressive strength depending on mortar age is depicted in Fig. 5.

7 Conclusion and Outlook

The suitability of heterogeneous brick-containing construction waste as a feedstock to produce lightweight aggregates



Figure 4. Facade element made with infra-lightweight concrete manufactured by Beton und Naturstein Babelsberg GmbH.

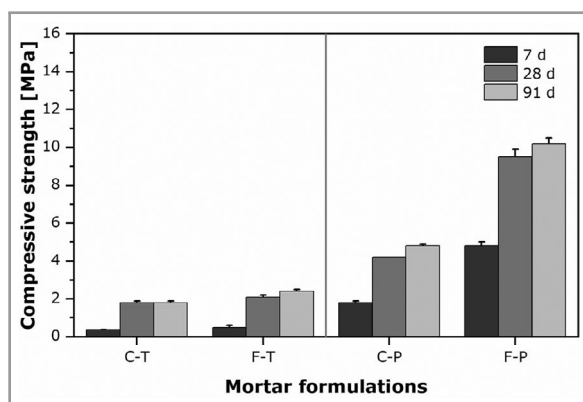
Table 4. Composition of lime-based repair mortars in vol.-% of dry mixture [21, 27].

Material	C-T	C-P	F-T	F-P
CL 90	22.5	12.4	25.9	15.2
CEM I 42.5	–	12.4	–	15.2
Tuff powder	9.0	–	10.4	–
Tylose	0.7	0.7	0.7	0.6
Quartz 0.04–0.25 mm	45.1	49.5	–	–
LWA from masonry rubble ^{a)} 0–0.5 mm	22.7	25.0	23.6	23.0
LWA from masonry rubble ^{a)} 0.5–1 mm	–	–	22.1	23.2
LWA from masonry rubble ^{a)} 1–2 mm	–	–	17.4	22.9
Water/binder ratio	0.97	1.23	0.94	1.03

a) Manufactured by thermal process followed by crushing and screening. C = covering mortar, F = filling mortar, T = tuff, P = Portland cement.

in a multistage process has been repeatedly demonstrated in laboratory and pilot plant scale. The REALight project represents a further step in the scale-up of the manufacturing technology. For the first time, the possibility of sulfate removal has been studied in more detail. At the same time, the large quantities of LWA produced in the pilot plant make it possible to study the performance stability of the lightweight aggregates in a comprehensive test program. Practical use in bounded and unbounded applications is tested as well as the demonstration example of a facade element made with ILC.

Incorporating new mineral residues as raw material or bloating agent can help to improve the economics of the technology. The research work of REALight project is to be continued. The focus is on the performance stability of the novel lightweight aggregates according to DIN EN 13055 [29]. Different batches of lightweight aggregates are tested to prepare product data sheets. In addition, basic research on the bloating behavior of different raw material mixtures

**Figure 5.** Development of compressive strength of lime-based repair mortars up to 91 days (C = covering mortar, F = filling mortar, T = tuff, P = Portland cement).**Table 5.** Project partners and main tasks in REALight.

Partner	Main tasks
Bauhaus-Universität Weimar	Coordination and material testing
IAB Weimar Institute of Applied Construction Research gGmbH	Pilot plant, LWA production and characterization, thermal treatment, and blowing studies
Bundesanstalt für Materialforschung und -prüfung (BAM)	Type testing of LWA, environmental compatibility, application studies repair mortars and concrete
Technische Universität Clausthal, IFAD	Extension of raw material base
T.B.R. Teltower Baustoffrecycling GmbH	LWA for garden and landscape constructions
Mendiger Basalt Schmitz Naturstein GmbH & Co. KG	Residual mineral materials
Beton und Naturstein Babelsberg GmbH	Lightweight concrete, demonstration concrete elements
Sievert Baustoffe GmbH & Co. KG	LWA in dry mortar and mortar systems
Heidemann Recycling Thüringen GmbH & Co. KG	Construction and demolition waste (CDW)
Opus Denkmalpflege GmbH	Repair mortar for preservation of historical monuments
IBU-tec advanced materials AG	Thermal process engineering
HanseGrand Klimabaustoffe e.K.	LWA in unbound systems

lead to a better understanding of the thermal conversion process and, thus, to adjust the properties of the lightweight aggregates in a more targeted manner.

Tab. 5 provides an overview of all project partners in REALight.

Acknowledgment

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Abbreviations

CDW construction and demolition waste
FGD flue gas desulfurization

FTC freeze thaw cycles
ILC infra-lightweight concretes
LWA lightweight aggregates

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