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The manufacture of lightweight aggregates from recycled masonry rubble

A. Mueller [a,*], A. Schnell [b], K. Ruebner [c]

[a] IAB – Weimar Institute of Applied Construction Research, Ueber der Nonnenwiese 1, 99428 Weimar, Germany
[b] Faculty of Civil Engineering, Bauhaus University Weimar, Coudraystr. 7, 99423 Weimar, Germany
[c] BAM Federal Institute for Materials Research and Testing, Unter den Eichen 87, 12205 Berlin, Germany

HIGHLIGHTS

- Heterogeneous and fine-grained masonry rubble as feedstock for the production of lightweight aggregates.
- Results of experiments on the conditions for the manufacturing.
- Results of the experiments on the technical and environmental characterization of the material.
- Concrete production in laboratory and technical scale.
- Outlook on technology, energy consumption and further suitable feed materials.

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ABSTRACT

At present, heterogeneous and fine-grained masonry rubble can only be recycled at very low level. To overcome this limitation, the material was employed as feedstock for the production of lightweight aggregates in a thermal process similar to that used in the manufacture of expanded clay and expanded slate. To that end, the fundamental suitability of masonry rubble as a raw material was evaluated. Experiments were carried out which indicated that lightweight granules with defined, adjustable properties similar to those of natural-material-based aggregates could be manufactured from masonry rubble. Structural lightweight concretes produced with these secondary aggregates achieved comparable performance to lightweight concretes produced with conventional expanded clay. Lightweight recycled building material aggregates represent a product that hardly requires any primary resources in its manufacture. In principle, the technique also seems to be well suited for high-quality recycling of other mineral waste materials.

1. Introduction

At present, the mix of various wall construction materials, mortar, plaster, and further components that make up recycled masonry rubble cannot be adequately utilized. This results from the considerable heterogeneity of the material composition and the large proportion of fines. In Fig. 1 a typical input pile of masonry rubble consisting of clay brick, other masonry blocs and a fine unidentifiable fraction is shown. For this material, there are no suitable recycling options. On recycling facilities the temporarily stored amounts of masonry rubble grow. The dumping fees increase or the acceptance is completely denied.

In the future, strict closed-loop recycling laws and limited landfill capacity will prevent the disposal or application of these materials as fill or in the construction of landfills completely. In this context, a technology for the manufacture of lightweight aggregates from masonry rubble was developed as part of a joint research project. These lightweight construction aggregates are produced from mineral construction waste and can be employed in the manufacture of lightweight mortars and concretes.

To date, lightweight aggregates have been primarily manufactured from natural resources. In areas with a volcanic history, that includes naturally occurring stone such as pumice, tuff, and lava. These materials are quarried and processed for use as lightweight aggregates for the manufacture of mortar and concrete. Other lightweight aggregates are produced synthetically, through a thermal technique – analogous to the natural process – that expands and stabilises the granulate material. Clay and slate that meet

* Corresponding author.
E-mail address: a.mueller@iab-weimar.de (A. Mueller).

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Fig. 1. Example for the input pile of masonry rubble at a recycling plant.

the following requirements are natural raw materials for these synthetic lightweight aggregates:

– When heated, the material must achieve a pyroplastic state with a favourable viscosity.
– A quantity of gas sufficient for pore formation must develop within the pyroplastic temperature range.

Industrial by-products are another source of raw materials for the manufacture of lightweight aggregates. Well known examples include coal fly-ash and bottom ash from power plants, which can be directly employed following mechanical processing. Recovered glass can also be used as a feedstock for lightweight aggregates [1–3]. Following the grinding process, it must be run through a shaping and firing process as well. Additional industrial by-products under consideration for the manufacture of synthetic lightweight aggregates, as described in the technical literature, include:

– Coal wash waste and flotation residues from coal processing, as well as with the addition of red mud [4–6].
– Ash from combustion processes [7–10].
– Fine particle waste from pumice processing [11].
– Uncontaminated or contaminated sediments and sludge from rivers, lakes, and water reservoirs, as well as sewage sludge [12–18].

Thus, the raw materials are extremely diverse. They originate from different sectors of the waste industry. So far, building rubble has been missing from this range of materials, despite being quantitatively the dominant type of waste. Whether building construction and demolition wastes (CDW) can be used to manufacture lightweight aggregates, and thereby enable a closed cycle for fine-grained and heterogeneous materials, is the topic of the research presented in this paper.

2. Characteristics of masonry rubble

The quantity of masonry accumulated since 1950 in existing building stock in Germany is illustrated in Fig. 2 [19]. As of 2010, it had reached more than 2000 million tons. The actual quantity may be higher than this value, as the quantity of masonry already existing in the building stock in 1950 is not included in this estimate. The quantity of masonry rubble produced in the demolition and rehabilitation of buildings is in the order of magnitude of 20 million tons. Considering that 15 to 20 million tons of wall construction materials are produced annually, this is a notable potential source of raw materials.

In contrast to concrete rubble and unmixed clay brick rubble, masonry rubble consists of multiple components. As well as brick, other construction materials present can include calcium-silicate brick, aerated autoclaved concrete, precast concrete, or natural stone. Additional components can include lime mortar, lime cement mortar, cement mortar, interior and exterior plasters, insulation, tiles, and façade panels. Recycled aggregates manufactured from this material through comminution and screening can vary greatly in their composition. This has been confirmed by the results of sorting analyses of processed masonry rubble (Fig. 3). The brick and other ceramic material content vary between a minimum and a maximum of 24 and 92 mass% respectively, with a mean value of 50 mass%. Concrete and mortar are the second most dominant material group. The mean is 46 mass% with a range between 8 and 70 mass%.

Within a batch of material there may be a variety of building materials with greatly differing properties. This diversity of materials is reflected in the width of the frequency distribution of the particle density (Fig. 4). Even when materials with a particle density less than 1760 kg/m^3 are omitted, the range of the densities is 750 kg/m^3.

To date, the consideration of chemical composition as a characteristic of masonry rubble is rarely made. The exceptions are the works by [20,21] indicating the composition of pure bricks and other ceramic products. However, for the recovery as raw materials the composition of masonry rubble is particularly relevant. In order to make an initial assessment, the oxide composition of the unmixed primary components of masonry in the ternary system SiO_2–Al_2O_3–flux ($CaO + MgO + Fe_2O_3 + Na_2O + K_2O$) is recorded (Fig. 5). This system is used to assess raw materials for ceramic building materials, including those for the manufacture of expanded clay according to [22,23].

Mineral-bound building materials as aerated autoclaved concrete, calcium silica brick or concrete lie virtually along one line in an unmixed state. Their Al_2O_3 content has a mean value of 4 mass%. Pure, ceramic-bound building materials set themselves apart from mineral-bound materials through their distinctly higher Al_2O_3 content. In contrast, systematic differences in the Al_2O_3 content of mixed masonry rubble composed of brick, other coarse ceramics, concrete, and/or other building materials are not discernable.

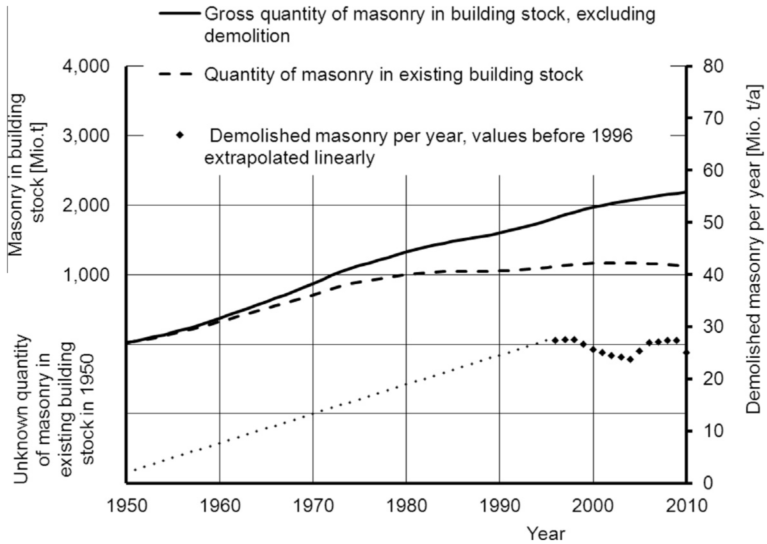

Fig. 2. Cumulative quantity of masonry in extant structures and quantity of masonry rubble arising from deconstruction and demolition [19].

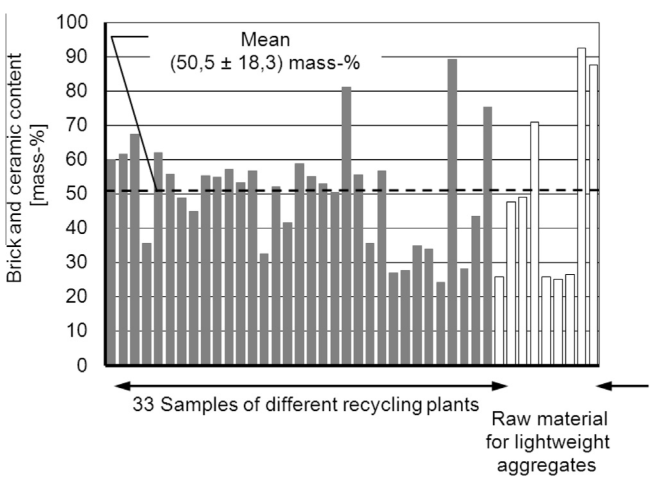

Fig. 3. Brick content of 42 masonry samples taken from processed masonry rubble piles at various stationary recycling plants including the used raw materials (own results).

With few exceptions, the composition of all 46 samples of masonry rubble analyzed fell into the marked area suitable for expanded clay production according to the literature. Thus, the reuse of masonry rubble using technology similar to that for expanded clay production is an alternative worth considering.

3. Manufacture of construction aggregates from masonry rubble

First, the conditions for manufacturing the lightweight aggregates were experimentally investigated. For that purpose, masonry rubble MW 1 with a brick content of 48 mass% (approximately the mean value given in Fig. 2) was crushed, ground to a particle size <100 μm, doped with an expanding agent, and granulated in a pelletier mixer. Subsequent the green granules are stabilised and at the same time expanded by a thermal treatment in a laboratory rotary kiln (Fig. 6). The influence of the firing temperature and the amount of added expanding agent on particle density and single grain strength were investigated. Following preliminary analysis, silicon carbide (SiC) was selected as the expanding agent.

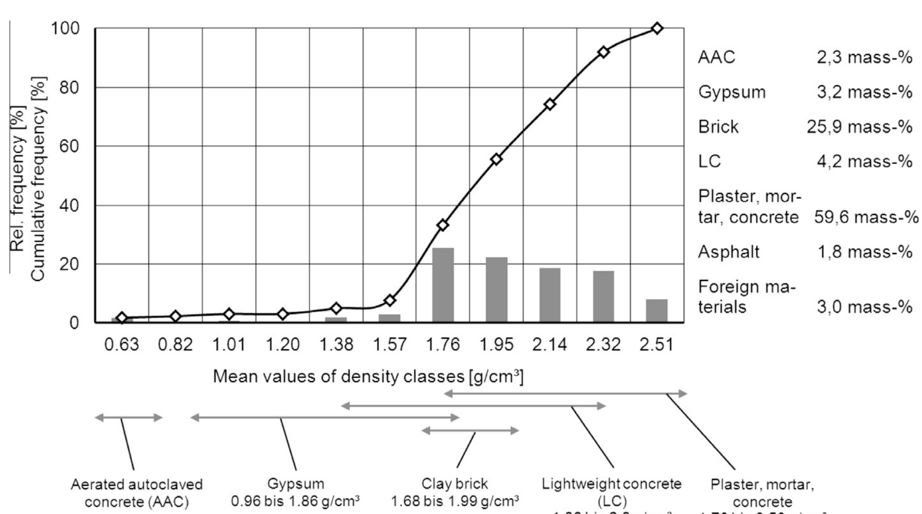

Fig. 4. Distribution of particle density (oven dry) of one of the masonry samples used for the production of lightweight aggregates from masonry rubble (own results).

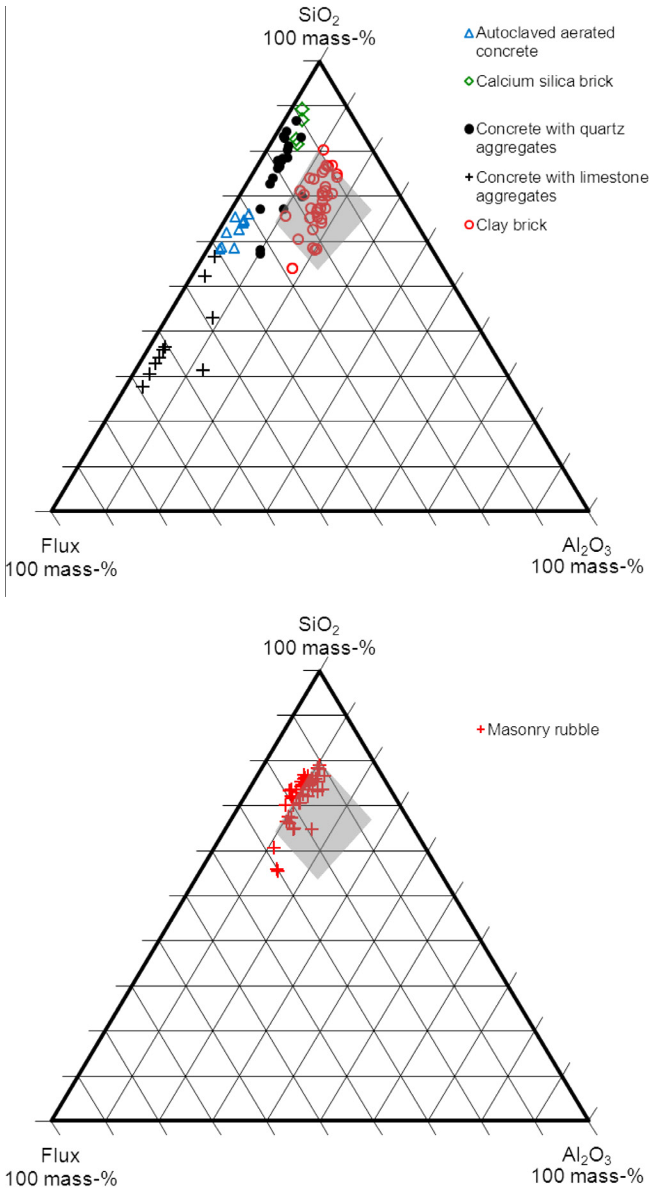

Fig. 5. Relative positions of the unmixed main components of masonry rubble and of real masonry rubble in the ternary system SiO_2–Al_2O_3–flux ($CaO + MgO + Fe_2O_3 + Na_2O + K_2O$) Gray area: [22,23]. Data points: own results.

The influence of the material composition of the raw materials was investigated in a second step. Five samples of masonry rubble were taken from recycling facilities. Their brick content varies between 0 and 80 mass%. The material composition and the chemical composition of these raw materials for the manufacturing of the lightweight aggregates are given in Table 1.

The thermal treatment was carried out in a laboratory rotary kiln with the parameters shown in Table 2. The temperature profile in the kiln and the kiln outlet are shown in Fig. 7. The residence time of the material in the kiln was about 8 min. The residence time at temperatures >1100 °C was only 3 min. In order to realize a higher residence time, the granules were thermally treated two times partly.

The following methods were used for the characterization of lightweight aggregates produced:

- The particle density was measured with a powder pycnometer. It works on the principle of volume displacement of a "fluid-like" powder [24]. The volume of the sample equates to the volume of the displaced powder, which is distributed and compacted around the sample by vibration in an automated measuring process.
- The single grain strength is determined using a pellet testing device. The grain of material is placed between a pressure plate and a punch and subjected to a linearly increasing load. The maximum force at the moment of failure is used as the measure of grain strength, applied over a circular area calculated from the diameter of the (presumed) spherical particle. A comparison with the grain strength measured at a defined particle bed with a pressure plate showed a satisfactory agreement.

As the results in Fig. 8 shows, increased firing temperature results in a reduction in particle density of the lightweight aggregates. Grain strengths for all of the granules follow a maximum function, whereby the maximum value for both particle fractions was achieved with a firing temperature of 1120 °C. The lowest density (1000 kg/m^3) was achieved at firing temperatures of 1160 °C and 1180 °C. For the 2/4 mm material, a further increase in firing temperature resulted in slightly higher density. However, this effect was not observed for the 4/8 mm material, as no recoverable granulate could be produced at the maximum firing temperature of 1200 °C. The granules began to melt and the grains adhered to each other.

The influence of the silicon carbide content on the expansion process was analyzed for a firing temperature of 1180 °C (Fig. 9). Green granules with differing SiC content were fired either once or twice in a rotary kiln. Double-firing is intended to extend the exposure time at a firing temperature above 1000 °C, which is otherwise restricted by the length and inclination of the rotary kiln to approximately 3 min. The density of granulate subject to a single firing indicates that values below 800 kg/m^3 are already possible with a SiC content of 1 mass%, which doesn't change much after a second firing. Dosing with 3 mass% reduces the density further if the material is fired a second time. Densities at or even below 600 kg/m^3 are achievable. Thus, the exposure time in the oven must be adjusted to correspond with the SiC dosing.

The influence of the brick content of the masonry rubble on the density of the lightweight aggregate is illustrated in Fig. 10. Even 20 mass% brick content allows aggregate with a density below 1000 kg/m^3 to be manufactured under laboratory firing conditions.

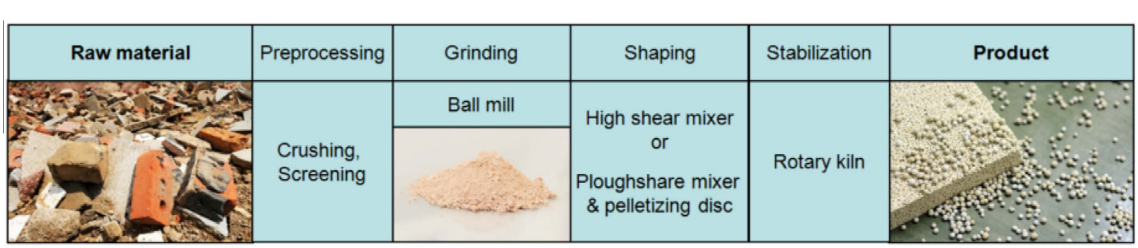

Fig. 6. Process scheme for the manufacture of lightweight aggregates from masonry rubble.

Table 1
Material and chemical composition of the masonry rubble used as raw material.

	MW 0	MW 1	MW 2	MW 3	MW 5	MW 9
Material composition and density						
Concrete and natural aggregates [mass%]	48	40	40	23	49	3
Clay brick [mass%]	26	48	49	71	26	92
Other mineral components [mass%]	19	11	9	5	19	4
Impurities [mass%]	7	1	1	1	7	0
OD particle density [kg/m^3]	1950	2420	2360	2390	–	–
Chemical composition [mass%]						
SiO_2	72.4	68.9	70.3	71.1	67.7	76.7
Al_2O_3	10.6	12.0	11.7	8.6	9.7	10.8
Fe_2O_3	2.0	3.7	2.2	1.8	3.2	5.3
CaO	10.2	9.2	8.2	11.4	11.1	1.6
MgO	1.3	2.3	1.6	1.5	1.8	1.2
K_2O	0.9	1.6	2.6	2.2	2.5	2.2
Na_2O	0.1	0.7	1.2	2.0	0.7	0.5
SO_3	2.0	0.7	1.1	0.4	1.7	0.3
Cl^-	0.03	0.02	0.03	0.02	0.02	0.02

Table 2
Technical parameters of the laboratory rotary kiln.

Type	Electrically heated ceramic tube
Diameter	100 mm
Length	2000 mm
Heated length	1000 mm in 3 heating zones
Through put	1–3 kg/h

The lowest densities were achieved with brick contents between 40 and 70 mass%. It appears that densities increase above 70 mass%. Overall, the aggregate seems to be relatively robust in relation to fluctuations in the brick content of the initial material. Increases in density at high brick content – atypical for masonry rubble – requires further clarification through further measurements. A conclusive explanation is still pending.

As a conclusion from the experimental results can be derived that masonry rubble is suitable as raw material for the manufacture of stable granules with a density of 1800 kg/m^3, if no expanding agent is added. In order to achieve lightweight aggregates, an expanding agent must be added that causes the formation of pores. SiC is suitable for this purpose. With an addition of 3 mass% SiC, the bulk density of the granules drops to 600 kg/m^3. The firing temperature must be within the range of 1100–1180 °C. The residence time at these temperatures must be at least 6 min. The content of clay brick in the used masonry rubble is not critical to the quality of the lightweight aggregates.

4. Properties of the lightweight aggregates

The properties of the manufactured lightweight granulates were assessed through a comprehensive experimental program. In addition to determining bulk, particle and true densities, the investigations included water absorption, chemical properties, and environmental compatibility.

If water absorption and particle strength are considered dependent on particle density (Fig. 11), the most important characteristic for the classification of lightweight aggregates, then the following statements can be made:

- The water absorption of the manufactured lightweight aggregates is comparably less than that of the expanded clays included in these analyses.
- In terms of particle strength, the manufactured lightweight aggregates did not differ from expanded clay.

The low water absorption can be explained in terms of the specific microstructure of the particles as shown in Fig. 12. Each particle is enclosed by a low-porosity cover. The interior of the particles consists of an open system of irregular macropores and cavities in the micro- and millimeter range. In particular, the large irregular pores interrupt capillary water transport within the particles, which results in the moderate macroscopic water absorption of the manufactured aggregates.

The particle density distribution of the manufactured aggregates shown in Fig. 13 is clearly narrower than the distribution of the used raw material (see Fig. 4). The spread is just 140 kg/m^3. The large proportion of particles with particle densities greater than 1000 kg/m^3 is probably due to the fact that the expansion process was not complete. A reduction in this fraction can be expected following an additional firing.

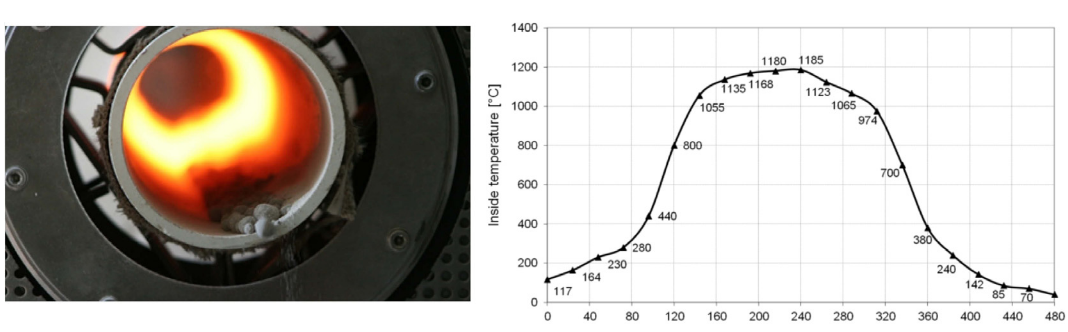

Fig. 7. Kiln outlet and temperature profile in the kiln.

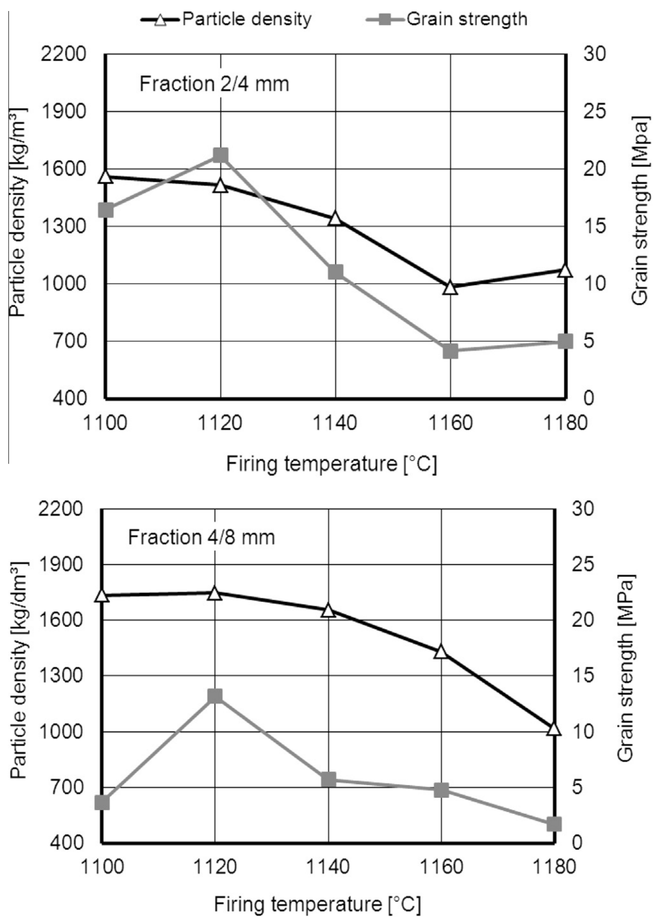

Fig. 8. Influence of the firing temperature on the particle density and the grain strength of expanded granules produced from masonry rubble MW 1 with 48 mass% clay brick, dosed with 3 mass% SiC.

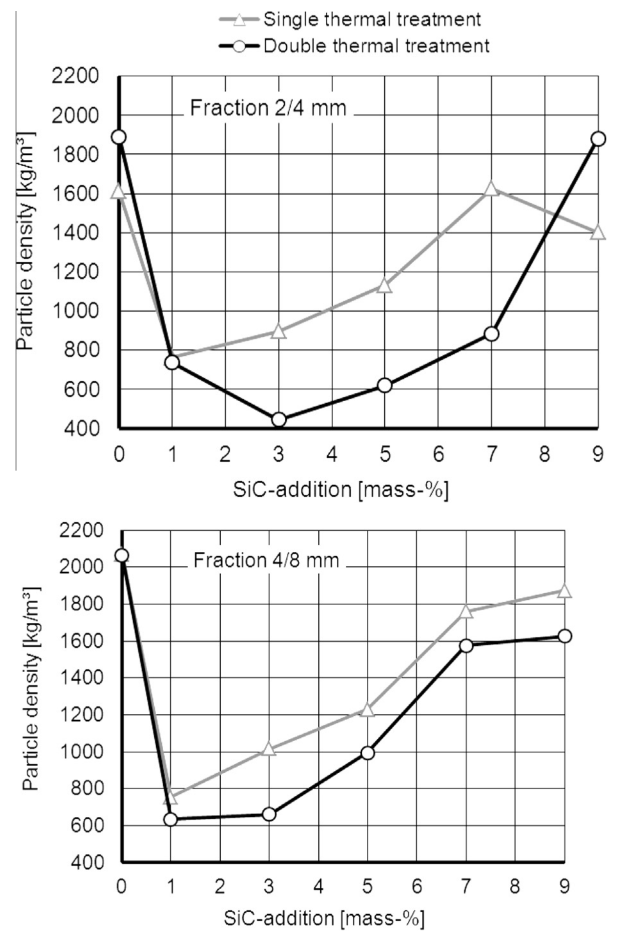

Fig. 9. Influence of SiC-dosage on the particle density of expanded granules produced from masonry rubble MW 1 with 48 mass% clay brick, fired at a temperature of 1180 °C.

The aggregates produced meet the specifications for the chemical properties of aggregates and the required environmental parameters. The contents of water-soluble chloride, acid-soluble sulfate and total sulfur were tested according to DIN EN 1744-1 [26]. To evaluate the environmental compatibility, harmful inorganic components were analyzed in the solid samples as well as the aqueous leachates. Figs. 14 and 15 shows the relative salt, arsenic and heavy metal contents of various lightweight granulates referring to the relevant limits that are set as 100%.

5. Manufacturing concrete from lightweight aggregates

Extensive analyses of lightweight concretes with dense structure were undertaken in order to verify the applicability of the lightweight aggregates [27,28]. The aggregates used for the concrete were produced in the laboratory and in small-scale trials.

The lightweight concrete was manufactured with aggregates with a grading that fits the AB8 line, 450 kg/m^3 CEM I 32.5 R cement, and a water-cement ratio of 0.45. The 2/4 mm and 4/8 mm particle size groups consisted of both the manufactured lightweight aggregates for testing and commercially available expanded clay with similar density as a control. In each case, they accounted for 54 vol.-% of the aggregates used. The particles smaller than 2 mm consisted of natural sand. The porous granulates were pre-moistened to account for additional water absorption. The absorbed water – 70% of the 60-min water absorption – was added along with the mixing water.

In terms of its mechanical strength and modulus of elasticity, concrete produced with the newly developed lightweight aggregates had similar values to the comparison concrete produced from conventional expanded clay (Fig. 16).

With 28-day compressive strengths between 35 and 50 MPa, the lightweight concretes can be assigned to the LC 25/28 and LC 35/38 strength classes according to the standard DIN EN 206-1 [29]. Oven-dry densities between 1660 and 1760 kg/m^3 identify the material as a D1.8 class lightweight concrete. These lightweight concretes typically have a total porosity between 30 and 35%. The static modulus of elasticity ascertained for concrete cylinders increases slightly with increasing density from 18 to 22 GPa. Further properties of hardened concrete manufactured with the new aggregates are also comparable with those for concrete containing conventional expanded clay. For example, the shrinkage behavior of lightweight concretes specimens containing aggregates made from masonry rubble is almost identical to those of the comparative concretes as shown in Fig. 17. At the age of 91 days, the shrinkage exceeds about −0.8 mm/m, which is acceptable due account of used testing conditions [27]. Furthermore, the carbonation rate of concretes containing lightweight aggregates from masonry rubble is as high as the comparison concretes with expanded clays or natural gravel. The mean values of carbonation depths are shown along the square root of time in Fig. 18. As expected, the carbonation behavior is not deteriorated due to the high porosity of lightweight aggregates. A dense aggregate/cement paste interfacial zone is considered to be the reason for the high durability of the lightweight concrete. The carbonation depth would reach the critical value of 20 mm after 6–7 years supposing that the linear correlation with the square root of time is valid for a longer period.

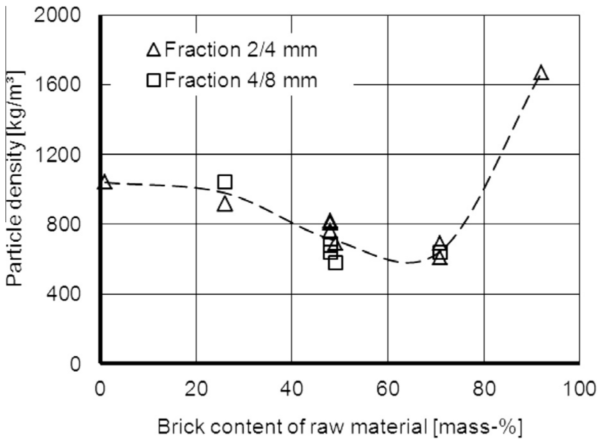

Fig. 10. Influence of the brick content of the input material on the particle density of the expanded granules produced from masonry rubble, under the following conditions: SiC-dosage 1 or 3 mass%, firing temperature 1165–1180 °C (values from [25], among others).

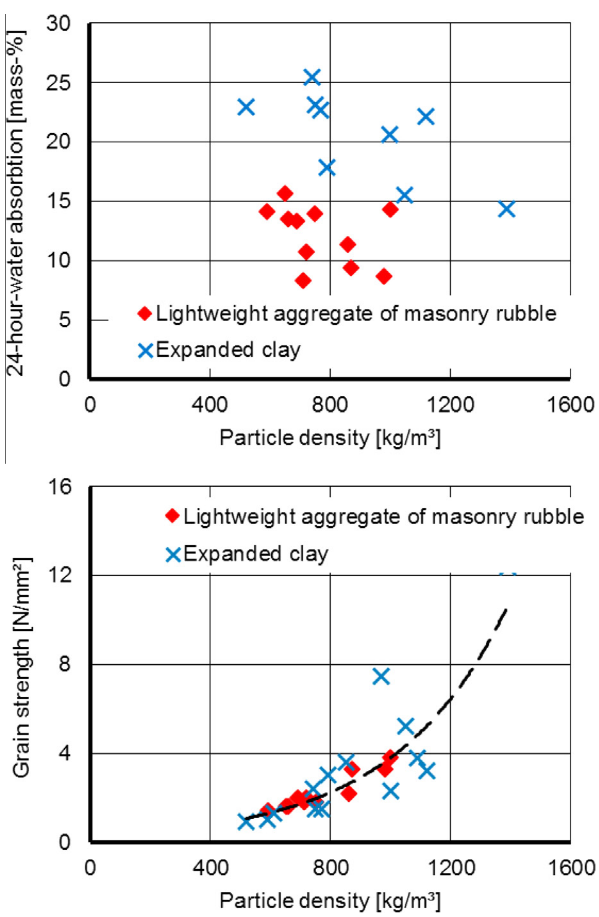

Fig. 11. Dependence of water absorption and grain strength on particle density, comparing lightweight aggregates from masonry rubble with expanded clay.

Estimating these results, it has to be considered that the carbonation rate is much slower under outdoor weathering then under laboratory conditions.

Lightweight concrete elements were produced in a concrete plant under practical conditions using lightweight aggregates (particle size groups 2/4 and 4/8 mm) manufactured from masonry rubble. Conventional expanded clays with a similar density were once again used as a control (see Fig. 19).

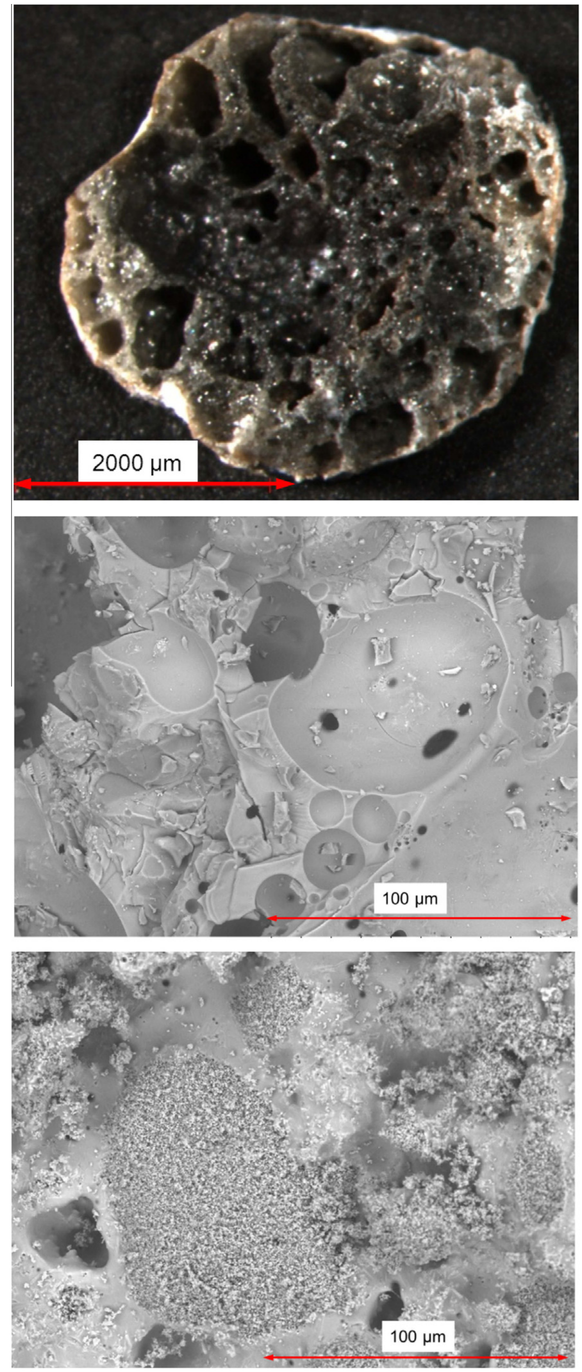

Fig. 12. Overview image of the fracture surface of an expanded granule (top) and micrograph of the surface (middle) and the inside (bottom) of the granule. Provided by Alexender Schnell (top), Steffen Liebezeit (middle, bottom).

The manufactured aggregates produced fresh and hardened concretes with properties on par with those made from expanded clays.

6. Potential as construction aggregate

From all tested properties, it follows that the lightweight aggregates from masonry rubble have a great potential as aggregates in construction industry. They can be used as aggregates for struc-

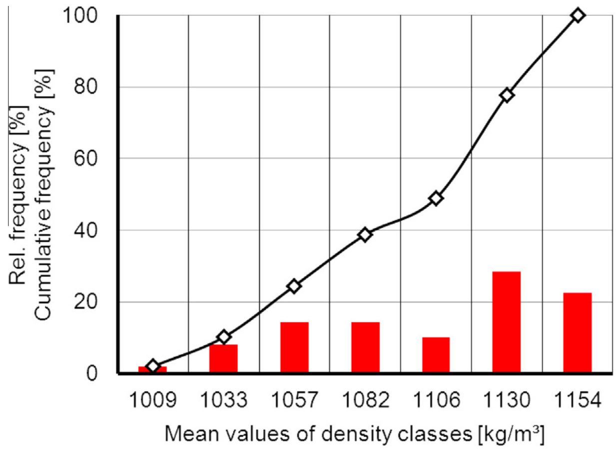

Fig. 13. Particle density distribution of the lightweight aggregates from masonry rubble with 48 mass% brick, fired once.

tural lightweight concrete as well as for concrete blocks or elements. Because of their low thermal conductivity, the aggregates from masonry rubble are also useable as bulk insulation material.

Manufacture of the lightweight aggregates can be accomplished using expanded clay production technology, according to the primary process steps illustrated in Fig. 20. It begins with the treatment of masonry rubble, similarly to the process used in the recycling industry. The material is then stockpiled, and can be homogenized at the same time. Manufacture of the aggregates themselves begins with grinding. After addition of the expanding agent, the powdered masonry rubble is granulated. Experiments show that pelletizing mixers, pelleting presses, and pelletizing disks are suitable [30]. Thermal stabilization and expanding in a rotary kiln follow. In the subsequent cooler, the sensible heat of the granules is used to preheat the combustion air. An application of an inert release agent is necessary. After leaving the cooler the expanded granules are graded to recover the release agent at least partially. The various process steps could be separated and distributed across several different locations. Preparation of the crushed masonry rubble could be achieved at recycling plants. Manufacture of the green granulates does not necessarily need to be at the location of the rotary kiln. The most appropriate solution will depend on adapting to regional constraints.

In terms of consumption of primary resources, manufactured lightweight aggregates from masonry rubble presents a nearly "primary resource free" product. Only the expanding agent and the release agent, which are partially consumed in the thermal process, need to be added. Silicon carbide, which is otherwise a waste product of sanding and cutting processes, could be employed as an expanding agent.

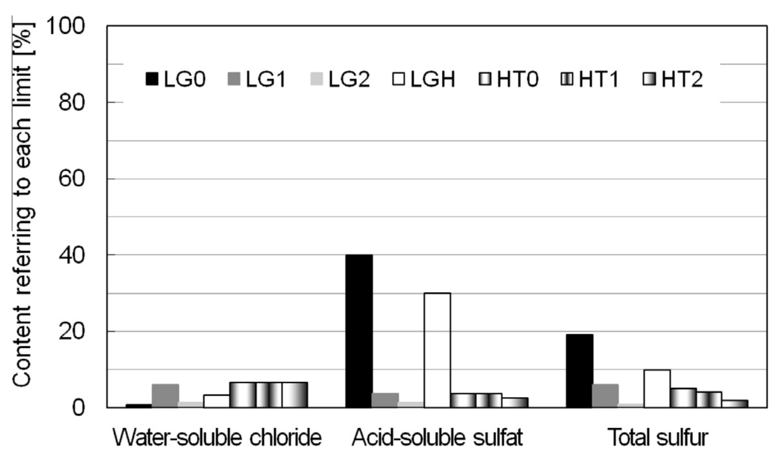

Fig. 14. Content of chloride, sulfate and total sulfur of various lightweight aggregates referring to the relevant limits that are set as 100% (LG: lightweight aggregates produced in the laboratory; HT: lightweight aggregates produced by small-scale manufacturing).

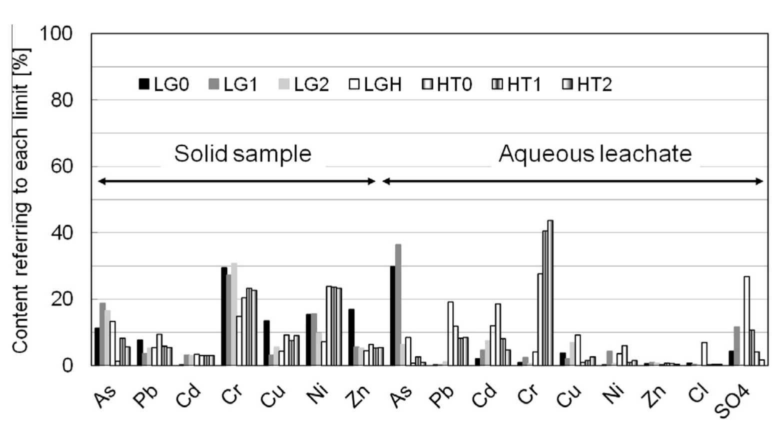

Fig. 15. Content of arsenic, heavy metals and salts of the solid sample and the aqueous leachate (batch test with liquid/solid ratio of 10 to 1 kg) of various lightweight aggregates referring to the relevant limits that are set as 100% (LG: lightweight aggregates produced in the laboratory; HT: lightweight aggregates produced by small-scale manufacturing).

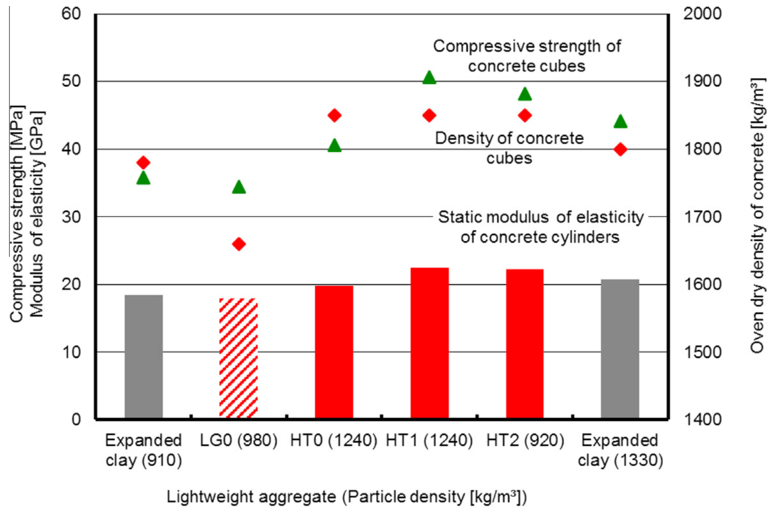

Fig. 16. Mechanical properties of laboratory concretes produced using lightweight aggregates from masonry rubble (LG: lightweight aggregates produced in the laboratory; HT: lightweight aggregates produced by small-scale manufacturing).

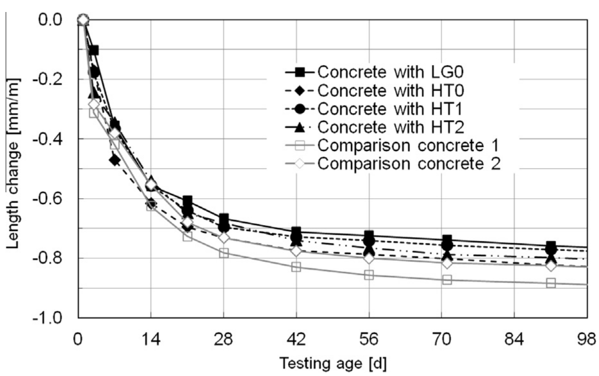

Fig. 17. Time dependant shrinkage behavior of different lightweight concretes with lightweight aggregates from masonry rubble measured at prisms of 40 mm × 40 mm × 160 mm stored at 23 °C and 50% relative humidity (LG: lightweight aggregates produced in the laboratory; HT: lightweight aggregates produced by small-scale manufacturing, comparison concrete with different expanded clays).

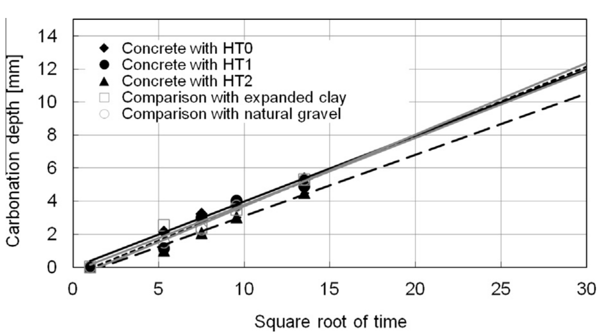

Fig. 18. Carbonation of lightweight concretes with different lightweight aggregates from masonry rubble measured at prisms of 40 mm × 40 mm × 160 mm stored at 23 °C and 50% relative humidity (HT: lightweight aggregates produced by small-scale manufacturing, comparison concrete with expanded clay and natural gravel).

The manufacture of conventional expanded clay serves as a reference for considering the energy consumption of the recycled material. Like the process described here, production is divided into the following steps: coarse crushing of the raw material, grinding, and granulation, followed by thermal treatment in a rotary kiln. Assuming that the 'cold' process steps don't differ in their energy demand, the thermal processes can be considered in terms of energy savings and additional energy costs (Table 3). The energy savings arise from the fact that the masonry rubble-derived material requires a lower water content for sharpening than clay. In addition, the energy costs associated with the dehydroxylation of the clay minerals can be saved, since this process has already taken place as part of the original brick manufacturing process. An additional energy consumption can result from calcium carbonate decomposition, if carbonised components from mortars and concretes are included in the masonry rubble. An initial assessment indicates that energy savings of approximately 15% are possible, taking calcium carbonate decomposition into account.

Various analyses indicate that an increase in gypsum content in demolition debris will need to be taken into account in the future [32]. As a result, sulfate reduction through mechanical detachment of gypsum plaster during demolition or in the course of processing is insufficient [33,34]. The manufacture of aggregates from recycled material could be used to effectively decrease the sulfate content in demolition waste, since gypsum can be thermally decomposed and subsequently recovered from the flue gas.

The manufacture of synthetic lightweight aggregates as per the process developed for recycling masonry rubble brings a range of further industrial byproducts and wastes into consideration. According to the survey in [35], the following materials are current topics of research:

- Coal wash waste and flotation residues from coal processing, as well as with the addition of red mud.
- Ash from combustion processes.
- Fine particle waste from pumice processing.
- Uncontaminated or contaminated sediment and mud from rivers, lakes, reservoirs, industrial processes, or sewage sludge.

The raw materials are extremely diverse. The principle of the technique appears to be predestined for the high-quality recycling of mineral wastes. Combined with the application of substitute

Fig. 19. Production of lightweight concrete blocks, left concrete block of lightweight aggregates from masonry rubble, right concrete block of lightweight aggregates from expanded clay.

Table 3
Comparison between the energy required for the manufacture of expanded clay aggregate vs. lightweight aggregates from masonry rubble, broken down by process step (basis information by [31]).

	[kJ/kg expanded clay]	[kJ/kg lightweight aggregate from recycled masonry rubble]
Heating process	1443	1225
Endothermic chemical processes		
Vaporisation of moisture	659	391
Dehydroxylation	241	0
Calcium carbonate decomposition	67	238
Calcium sulfate decomposition	0	37
Exothermic chemical processes		
	105	0
Total	2305	1891

fuels, which appears possible based on the required temperatures, a nearly primary resource and primary energy free technique could be developed.

7. Conclusion

The results of the project show strikingly that material that was previously only considered appropriate for low-value recycling can in fact be processed into a high value product, conditional upon the availability of the appropriate technology. A big advantage of the lightweight aggregate manufactured from masonry rubble is that the production process requires almost no primary resources. Industrial production of lightweight aggregates from recycled masonry rubble could provide the opportunity to replace natural pumice and expanded clays and reduce the use of natural resources.

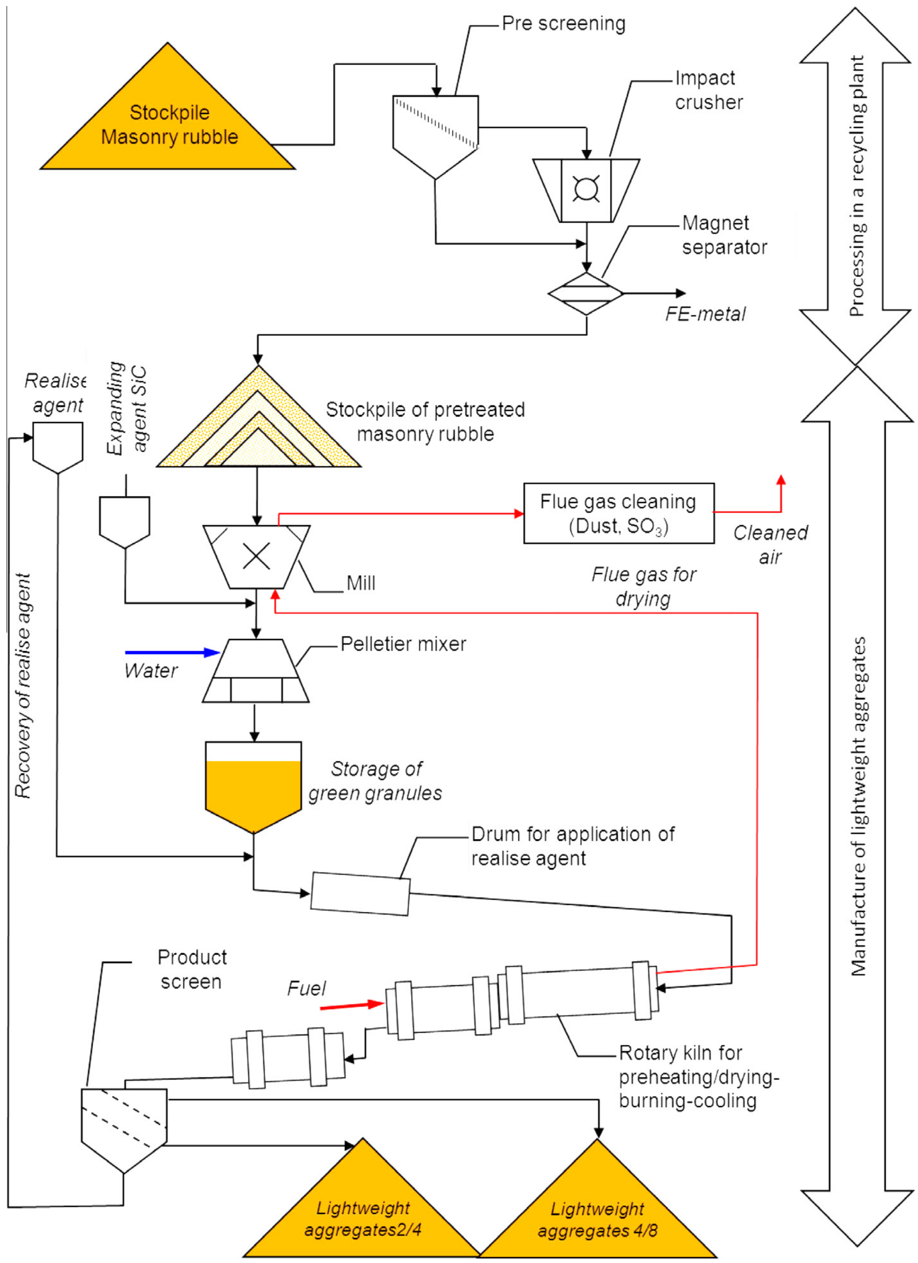

Fig. 20. Simplified manufacturing process for lightweight aggregates from masonry rubble.

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