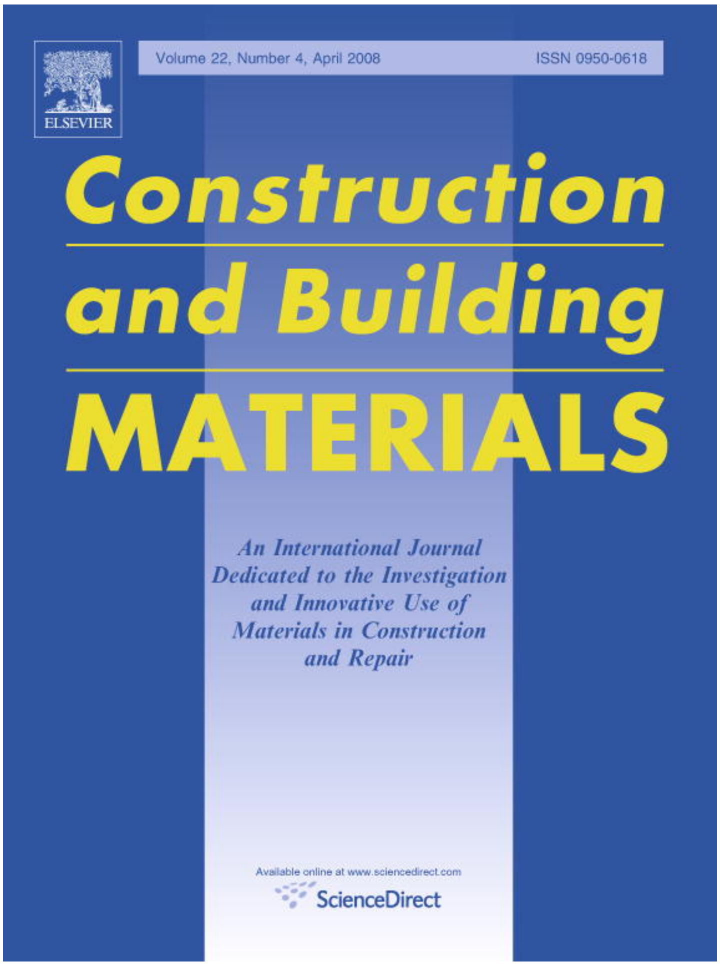
Volume 22, Number 4, April 2008
ISSN 0950-0618
ELSEVIER
Construction and Building MATERIALS
An International Journal Dedicated to the Investigation and Innovative Use of Materials in Construction and Repair
Available online at www.sciencedirect.com
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Construction and Building Materials 22 (2008) 703–712
Construction and Building MATERIALS
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Technical Note

Characteristics of lightweight aggregates from primary and recycled raw materials

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Received 13 March 2007; received in revised form 20 June 2007; accepted 22 June 2007
Available online 10 August 2007

Abstract

In the following, a brief survey of mineral lightweight granules manufactured on the basis of a wide variety of constituents is given. After that, research projects conducted at the Tomsk Polytechnic University (Russian Federation) and Bauhaus University Weimar (Germany) are introduced that focus on the development of lightweight aggregates from new raw materials sources. In Tomsk, zeolitic rocks were used, while the investigations in Weimar concentrated on the sand fraction of masonry rubble mixed with autoclaved aerated concrete.

Keywords: Lightweight aggregates; Building materials; Processing; Raw materials; Porous materials

1. Introduction

An analysis of the present tendencies in worldwide building activities shows that in design and construction of buildings of the next generation, specialists will make substantial efforts to minimize the weight of buildings. A solution of this task is particularly urgent in urban agglomerations where the lack of sufficient ground space forces builders to construct increasingly tall buildings. The use of appropriate heat insulation for residential and other buildings is linked to this problem. A possible way of reducing building weight and optimizing heat insulation is the application of lightweight granulates, both as a concrete aggregate and as a heat insulating fill.

Research projects conducted by the Tomsk Polytechnic University (Russian Federation) in cooperation with the Bauhaus University Weimar (Germany) are directed on the development of lightweight aggregates from new raw materials sources. In Tomsk, zeolitic rocks were used, while the investigations in Weimar were concentrated on the sand fraction of masonry rubble mixed with autoclaved aerated concrete.

2. Survey of mineral lightweight aggregates

2.1. Lightweight aggregates from natural raw materials

Natural raw materials suitable for manufacturing lightweight mineral granules are pumice, perlite, vermiculite, expandable clay and slate. The raw materials, with the exception of pumice, first undergo different conditioning processes to bring them into the desired initial stage. Subsequently they are subjected to a thermal treatment. In the course of the thermal treatment, gas is formed in the interior of the granules as a result of different decomposition processes. When the gas is restricted burst open and puff out – in a similar way as popcorn – forming of a porous structure results.

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doi:10.1016/j.conbuildmat.2007.06.009

Table 1
Properties of lightweight aggregates from natural and waste materials

Properties of lightweight aggregates	Lightweight aggregates from natural raw materials		Lightweight aggregates from waste materials			
	Perlite and vermiculate	Expanded clays	Granules of recycled glass	Granules from crushed sands	Mineral foam granules	Fly ash and adjustment components
Firing temperature (°C)	about 900	1100–1200	750–900	1000–1080	<1000	1000–1300
Bulk density (kg/m^3)	32–400	160–850	190–300	250–600	150–400	710–1400
Thermal conductivity (W/mK)	0.04–0.06	0.08–0.12	0.07	0.06–0.09	0.09	0.07

The temperature required for the thermal treatment depends on the gas formation reaction and the smelting behaviour of the initial constituents. According to these features the materials can be roughly broken down into two groups.

Raw materials of "glass-like" composition

- Perlite and vermiculate belong to this group. Perlites are made from volcanic raw perlite. Water enclosed in the rock puffs up the broken raw materials to roundish granules of 1–6 mm diameter. The following process and materials parameters and applications are described in the literature [1]:
  The products are used as thermal insulation in floors, as core insulation for bricks, as lightweight aggregate in mortars, renders and concretes.
  Raw materials of "clay-like" composition
- Expanded clays and slates belong to this group. The clays are primarily illitic clays. Here, organic carbons and/or iron hydroxides can cause the expansion process that leads to an increase in volume [2,3].

Similar to the first type, the products are used as thermal insulation in floors, as core insulation for bricks, as lightweight aggregate in mortars, renders and concretes, and as substrate in agriculture.

2.2. *Lightweight aggregates from waste materials*

In the manufacture of lightweight aggregates, a wide range of wastes are increasingly take over the role of raw materials. The following group of raw materials can be classified as being of glass-like composition:

- Granules of recycled glass [4–7]
  The recycled glass is processed into a powder, mixed with an expanding agent and then formed into granules.
- Granules from crushed sands obtained from pumice processing [8]
  The crushed sands, which have only a low porosity and therefore are primarily used for recultivating pumice opencast mining landscapes, is ground. The swelling process and the consolidation process take place during thermal treatment.
- Mineral foam granules [9]
  These lightweight aggregates are made from mineral materials, flux agents and foaming agents. After processing and after adding the constituent materials, the green granules are glassed and foamed. The bulk density can be influenced by the choice of raw materials and by the reaction materials.
- Foamed glass gravel [10,11]

Ground recycled glass is mixed with aggregates, fused and blown up at temperature from 700 to 800 °C during which process a closed structure is formed. After leaving the kiln, the product is crushed.

The second group of lightweight aggregates produced on the basis of waste materials includes products obtained from sewage sludges with the addition of clays. The production process comprises the following stages: mixing of components, shaping and burning in a rotary kiln or in a fluidized bed reactor. A detailed survey of these products is given in [12].

In a further group of lightweight aggregates, fly ash with residual carbon content of 3–5% is used as a constituent [13,14]. The fly ash and adjustment components, like e.g. bentonite or fine ground carbon, are mixed, pelletized and then sintered.

Properties of lightweight aggregates from natural and waste materials are shown in Table 1.

3. Expanded granules from zeolitic rocks

Investigations performed in Italy and in Russian Federation have shown that high-grade granulate expanded materials can be produced on the basis of zeolitic rock, using temperatures between 1150 and 1200 °C, including rocks with an average and low zeolitic content of 10–50% [15–23]. The main objective of these investigations was the development of a low-temperature-technology (up to 900 °C) for the production of lightweight granulated glassceramic materials from zeolitic rock and an assessment of the principal laws of the volume expansion occurring in zeolitic masses. In the following, the compositions and technological parameters will be described, which were used in the investigations to obtain lightweight glassceramic materials that offer a wide potential application spectrum for zeolitic rock.

3.1. Raw material

Zeolites are alkali and/or earth-alkali aluminosilicates. The structure of common zeolites is described by the following formula:

$$M_{2}/_{z}O \cdot Al_2O_3 \cdot xSiO_2 \cdot yH_2O,$$

where M the mono- or bivalent metal, mostly Na^+, K^+, Ca^{2+}, Mg^{2+}, Sr^{2+} or Ba^{2+}; z is the valence of the cation; x is the number of SiO_2 from 1.8 to approx. 12; y is the number of H_2O from 0 to approx. 8.

Zeolites have a unique set of properties which opened a broad range of traditional applications in the fields of adsorption, ion-replacement, catalytic processes and molecule differentiation [24–27]. One of the particularities of the zeolite is its ‘‘porous’’ structure. It is traversed by cavities and capillaries, whose formation can be explained by the substitution of Si^{4+} by Al^{3+} ions and the resulting necessity to compensate the negative residual charge of the ‘‘skeleton’’ through cation exchange processes.

The raw material used in this investigation was the zeolitic rock obtained from the Sachaptinskoje deposit in the region of Krasnojarsk (Russia). Mineral composition of the zeolitic rock from this deposit is presented by zeolites (clinoptillolite), quartz, feldspars and clay minerals (montmorillonite). By its chemical composition the zeolitic rock is close to glass composition with shortage of alkali content. Chemical composition of the zeolitic rock is shown in Table 2. Table 3 below summarises the chemical composition of the calcined soda that was used as an alkaline component in the present investigations:

3.2. Experimental process for production of granules

For preparing the raw materials mix, the zeolitic rock was ground in a ball mill to a particle size of ⩽250 μm. After adding up to 20% of soda ash (see Table 3) to increase the alkali content, the mixture was fritted at a temperature of 700 °C. The generated frit was then ground and an expanding agent was added. Then granules were formed from the so obtained intermediate product using a pan granulator. The granules were burnt in a muffle furnace, and afterwards cooled (Fig. 1).

As variables, the firing temperature and the amount of added soda were investigated. The bulk density, the water adsorption and the particle strength were determined on the so obtained expanded zeolites in accordance with the standardized Russian test method GOST 9758-86 [28].

Table 3
Chemical composition the calcined soda

Na_2CO_3	Chloride (NaCl)	Sulfate (K_2SO_4)	Fe_2O_3	Insoluble residue	Loss of ignition (270–300 °C)
99.0	< 0.5	< 0.05	< 0.003	< 0.04	< 0.8

3.3. Results

The main conditions that determine the suitability of a rocky material for the production of porous structure are a low melting temperature of the rock and the ability of the molten rock to expand and form a porous structure. With respect to the melting temperature, the zeolitic rocks resemble the low melting clays, where the melting temperature for the production of expanded-clay-materials ranges from 1100 to 1250 °C. Concerning the first condition zeolitic rock is thus comparable to alumosilicate rock which is adequate for the production of expanded clay and other porous materials.

In the first phase of the investigations, the influence of the amount of calcined soda on the properties of the granulated zeolite was investigated. The results are shown in Fig. 2. It can be seen that the granulated expanded zeolites with a soda ash content of 20% has the best combination of properties: Acceptable bulk density, low water adsorption and relatively high strength.

A microscopic insight into the internal structures of the granules with different content of the calcined soda is shown in Fig. 3.

The granules with 20% calcined soda content show a regular structure with closed pores. An increase of the calcined soda content entails an increase in pore size, and a reduction of pore wall thickness, two factors that lead to a reduction of the strength of the expanded zeolites.

The thermal behaviour of the zeolitic rock with 20% calcined soda added is described by the differential thermo analysis (Fig. 4). The heating rate adopted in the thermal (DTA) analysis was 20 °/min. The endothermic effect at 150.6 °C (DTA) is related to the extraction process of hydroscopic water up to 100 °C. The temperature range above 100 °C is characterized by the extraction of adsorbed water from the zeolitic materials (Klinoptillolit and Geilandit) and from the clay (Montmorillonit).

The endothermic effect in the DTG-curve at a temperature of 551.4 °C corresponds to the decomposition of clay materials and is coupled to a mass loss of 4.22% on the TG-curve.

One of the chosen expanding agents was anthracite. The DTA and TG curves of the frit with 1% of anthra-

Table 2
Chemical composition of the zeolitic rock from the Sachaptinskoje deposit in the region of Krasnojarsk

Oxide content (%)								
SiO_2	TiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	Loss of ignition
64.8	0.35	12.77	2.46	2.5	1.84	0.63	3.2	11.12

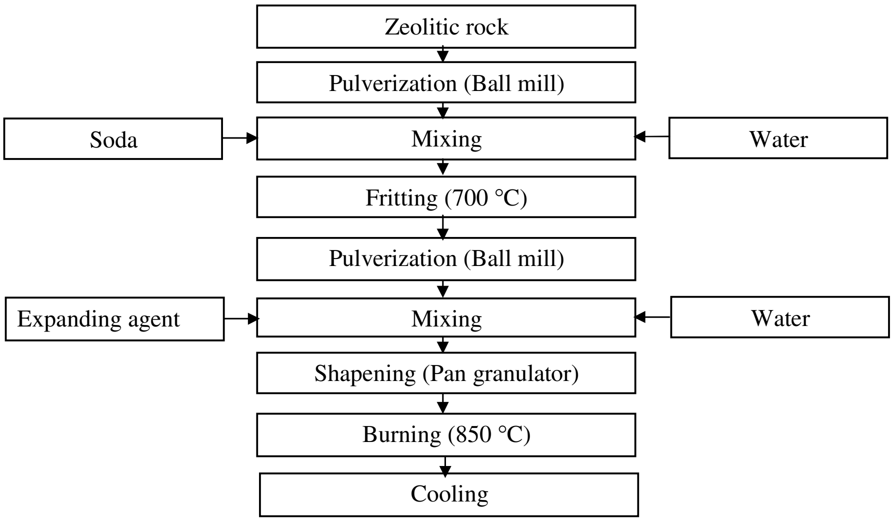

Fig. 1. Experimental process for expanded granule production from zeolitic rock.

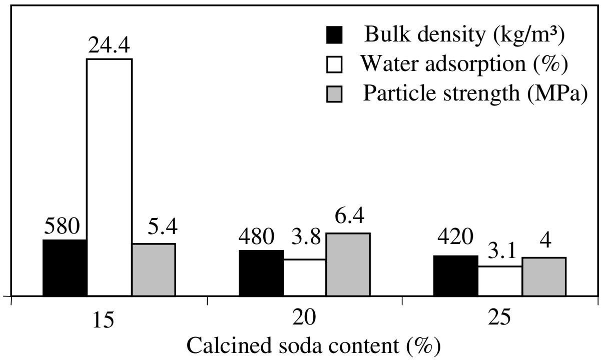

Fig. 2. Properties of the expanded zeolites as a function of calcined soda content.

cite are shown in Fig. 5. In the temperature range 100–135 °C adsorbed water is extracted from the dispersion system (DTA and DTG-curves). The exothermal effect at 552.8 °C (DTA) is caused by the burning of the anthracite. The resulting loss of mass is caused by the liberation of CO_2 and amounts to 1.91 %. The endothermic effect at 134.9 °C is caused by the evaporation of the water, which was added to produce granulates by the pan granulator. At fast heating rate of the zeolite samples the processes of gas evolution and melting coincide. In this way, the generation of a porous structure is achieved.

The next objective of the investigations was to assess the influence of the added amount of expanding agent and of the fineness of the frit on the properties of the expanded zeolites. The expanding agent addition ranged from 0.5% to 1.5%. The frit to which the expanding agent was added was ground to a maximum particle size of 90 μm. The results of these investigations are shown in Fig. 6. Using an anthracite content of 1%, an expanded zeolite with a bulk density of 460 kg/m^3 was obtained.

An impression of the pore structure inside these granulates is given by the microscopic pictures shown in Fig. 7. Granulates have cellular structure. The pore sizes lie within a broad range of 0.5–2.5 mm.

4. Expanded granules from masonry rubble

The starting point for this development was the low rates of reuse of the mixed sand fraction of construction and demolition waste, especially masonry rubble and used autoclaved aerated concrete. Recipes and technologies for the manufacture of expanded granules from these sources

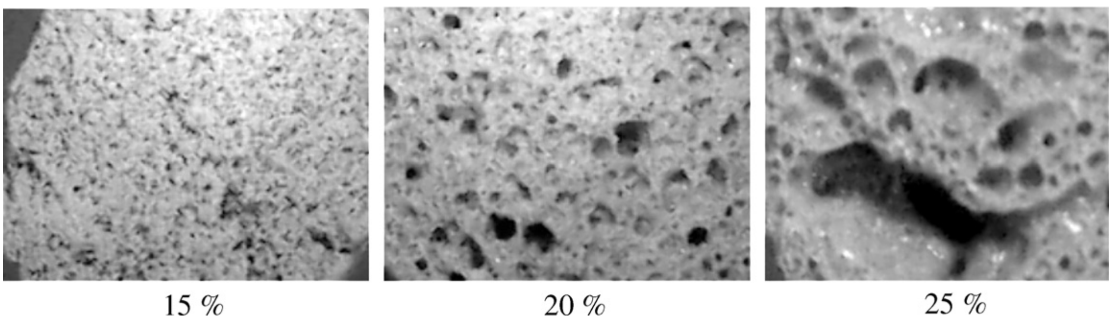

Fig. 3. Expanded zeolites with different amounts of added calcined soda.

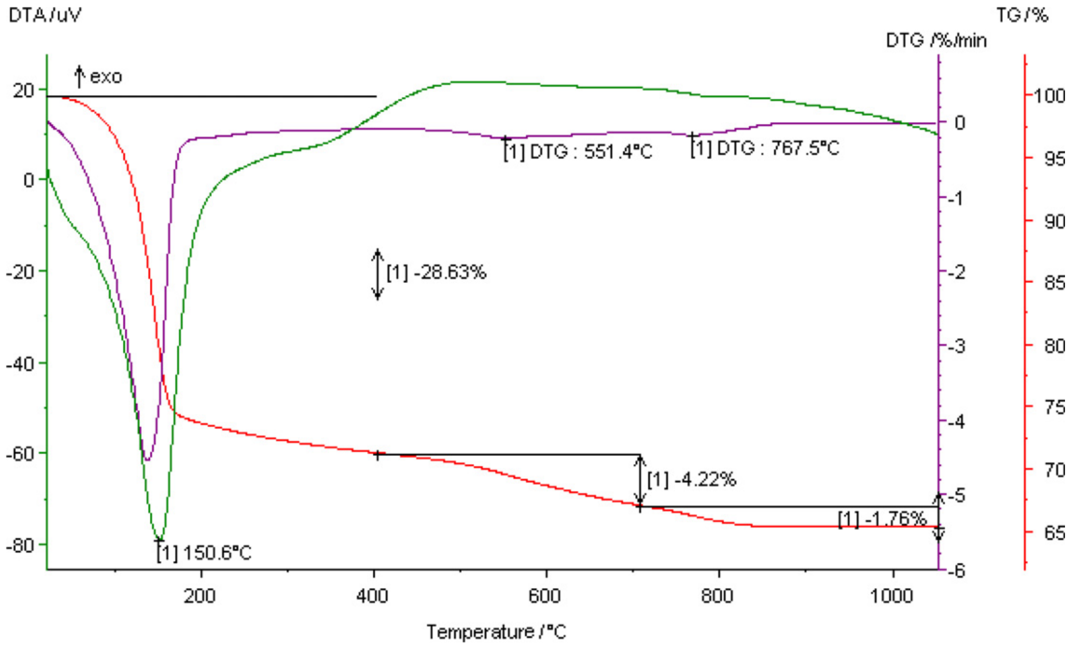

Fig. 4. DTA and TG curve of zeolitic rock with an addition of 20% calcined soda.

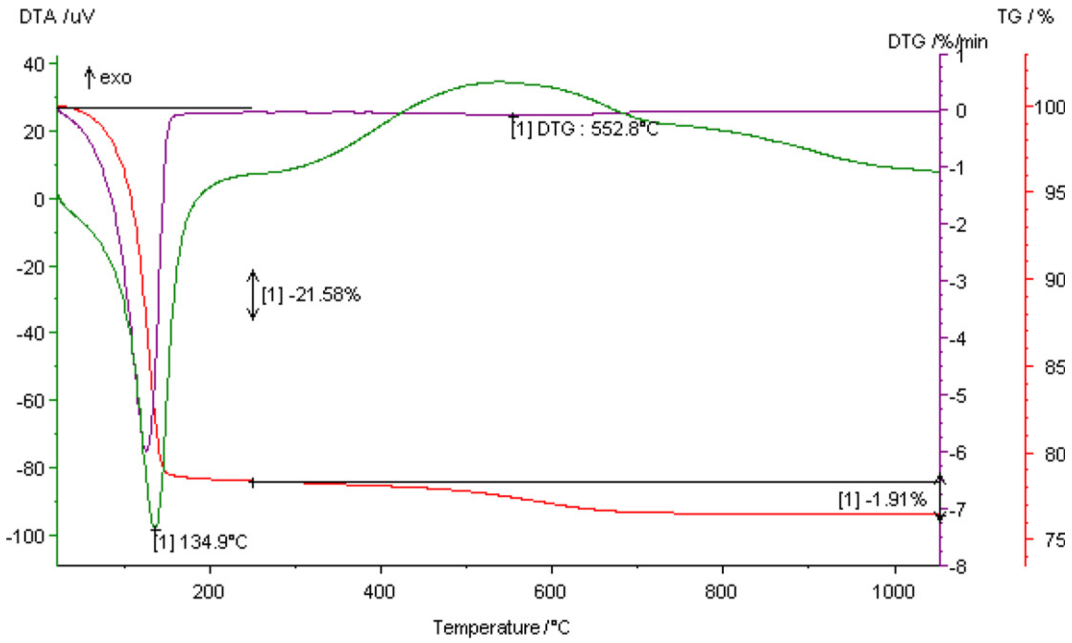

Fig. 5. DTA and TG curve of the frit with 1% of anthracite.

of secondary materials should be developed. Further it should be demonstrated that granulates are suitable as lightweight aggregate in concrete or as lightweight structural bulk material.

4.1. Raw materials

The investigations were performed on masonry rubble of fraction 0/4 mm from a recycling company. Autoclaved aerated concrete sand was used as a second component. The chemical composition (Table 4) illustrates the typical differences between the two constituents. In the masonry rubble, Al_2O_3 is the component with the highest content, if the SiO_2 is excluded from the considerations. In the autoclaved aerated concrete rubble, CaO is the dominant component after SiO_2.

The thermal behaviour of the both raw materials differ quite considerably (Fig. 8). The total mass loss of the autoclaved aerated concrete amounts 22.5%. While the mass loss observed at temperatures of up to about 100 °C are to be attributed do the evaporation of the adsorbed water, the loss at higher temperatures is caused by the

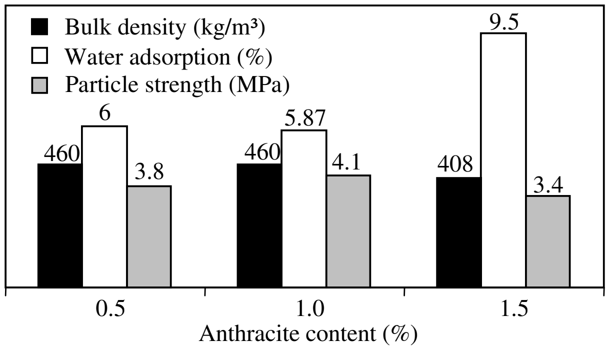

Fig. 6. Properties of expanded zeolites as a function of the expanding agent concentration.

decomposition of calcium silicate hydrate. The curves for brick show comparatively little temperature reactions.

4.2. Experimental process for production of granules

The technological procedure adopted for the investigations is presented in Fig. 9. The materials – masonry rubble and autoclaved aerated concrete wastes – were first separately ground to particle sizes <100 μm. Grinding was followed by mixing of the components, by addition of the expanding agent – suitable were e.g. silicon carbide (SiC) residues – and by granulation. In the follow thermal process the granules were expanded and solidified. In preliminary tests, the suitability of $CaSO_4 \cdot 2H_2O$, NaCl, beet

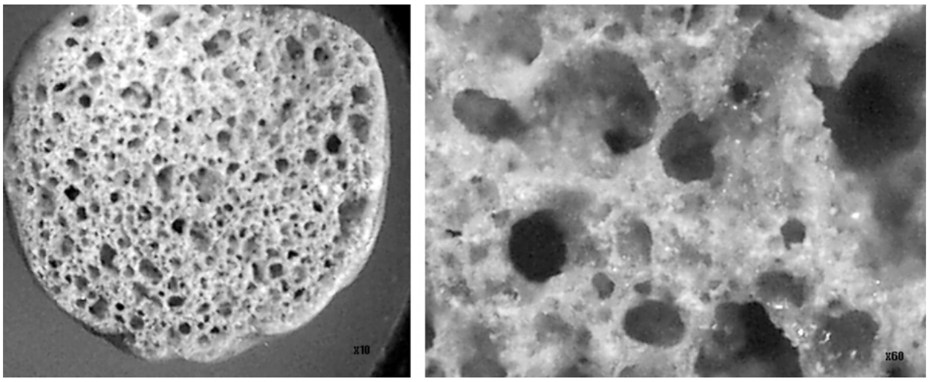

Fig. 7. Microscopic structure of the granulates with 1% anthracite addition.

Table 4
Chemical composition of the raw materials components

	Oxide content (%)							
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	Loss of ignition
Autoclaved aerared concrete rubble	43.6	3.6	1.7	30.1	0.8	0.5	1.9	15.1
Masonry rubble	56.1	15.7	5.8	5.0	2.8	0.9	3.5	2.6

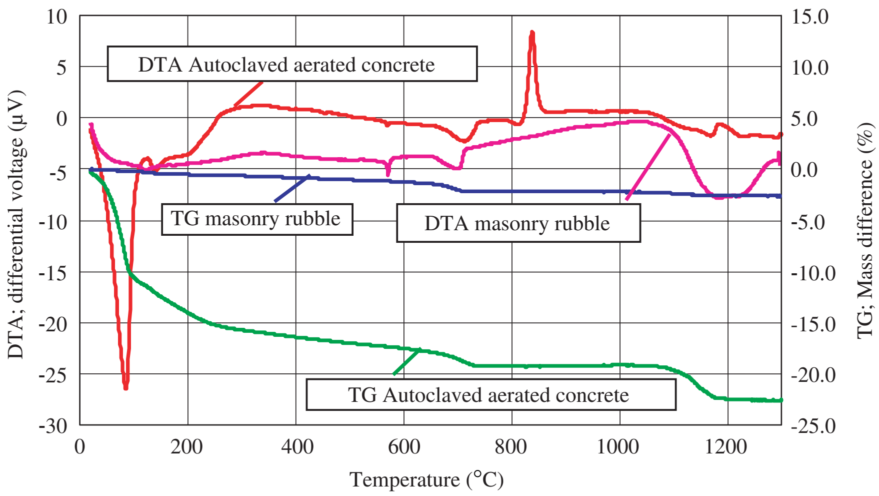

Fig. 8. DTA and TG- curves of the raw materials masonry rubble and autoclaved aerated concrete sand.

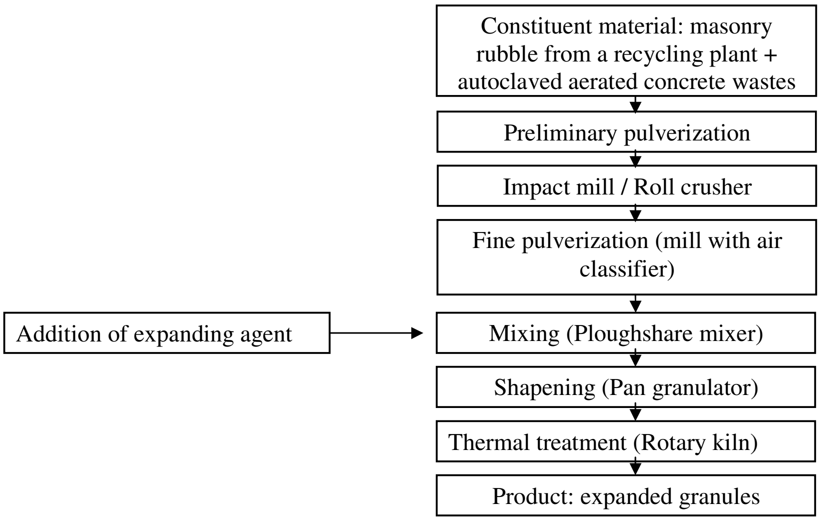

Fig. 9. Experimental process for expanded granule production from masonry rubble and autoclaved aerated concrete wastes.

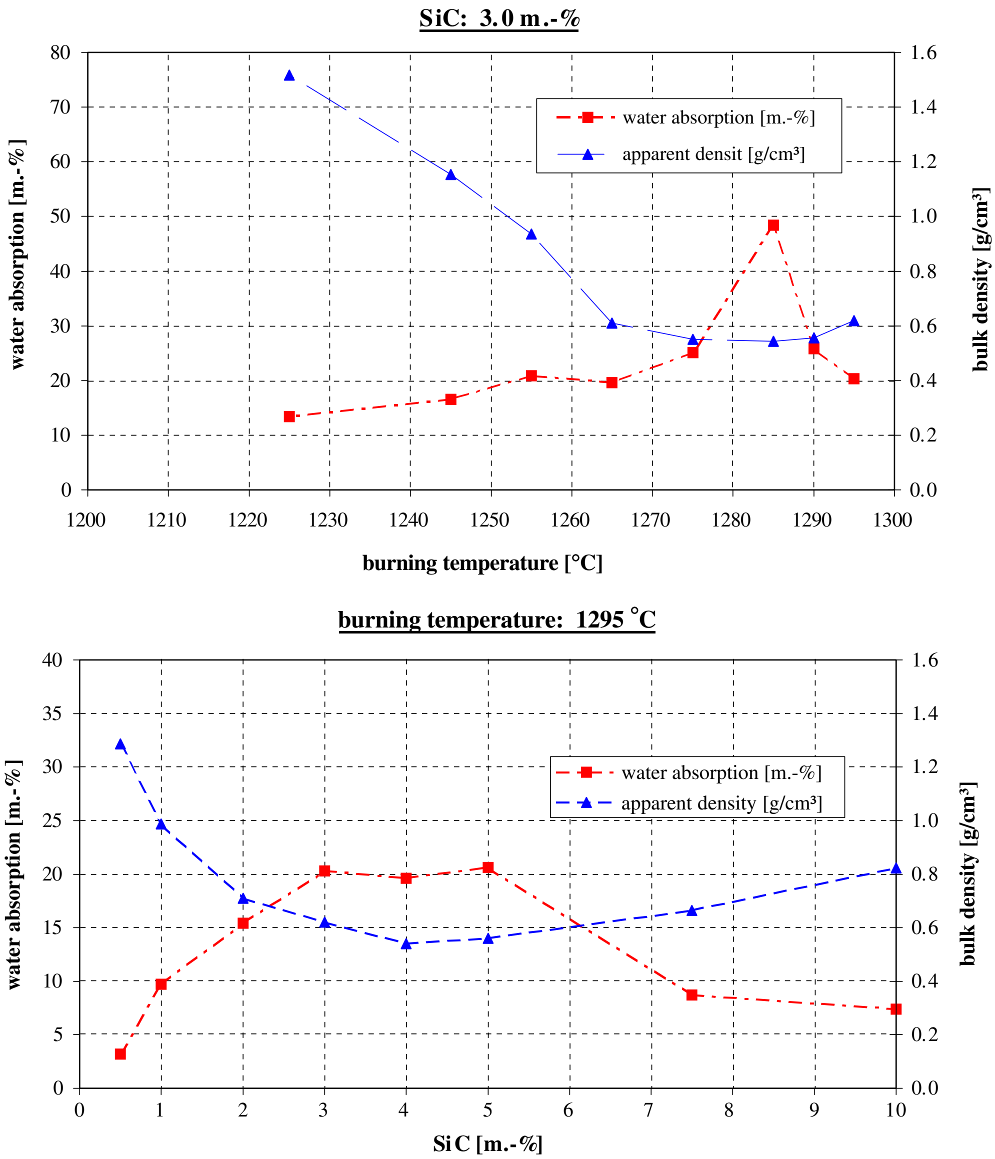

Fig. 10. Influence of the firing temperature (above) and the amount of SiC addition (below) on the particle density and water adsorption of the granules.

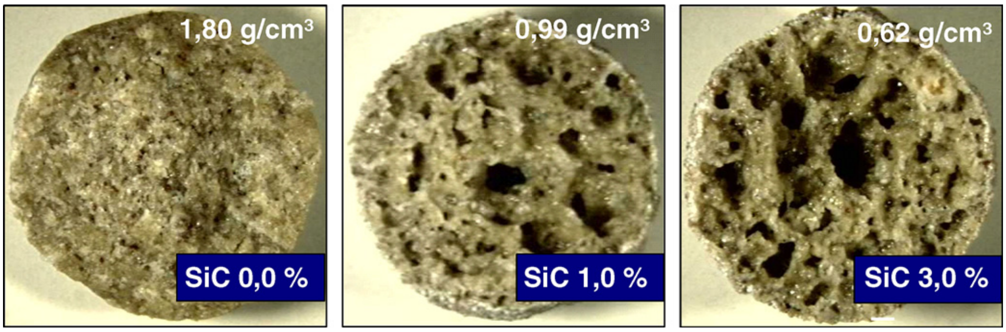

Fig. 11. Formation of the pores in the granules based on mixed from masonry rubble and autoclaved aerated concrete.

sugar, coke power and silicon carbide had been tested as expanding agents. The materials, pulverized to <100 μm, were added to the ground constituents in a proportion of 3%. In order to assess the effect of the expending agents, the particle densities of the burned granules were compared to the particle densities of green granules. A clear difference could be observed when SiC was added as expanding agent. Therefore, SiC was used as the only expanding agent for all subsequent testes.

The investigations were first performed to laboratory scale in order to determine the effects of the composition and the firing conditions on the properties of the granules. After that, a larger amount of granules was manufactured to pilot plant scale to be able to manufacture lightweight concrete blocks in a concrete plant.

4.3. Results

It could be shown that a mixture of the sand fractions from masonry rubble and autoclaved aerated concrete is suitable as raw material for the production of lightweight aggregates. The masonry powder content in the mix can be up to 100%, while the autoclaved aerated concrete powder content should not exceed 50%. The densities of the granules ranged between 530 and 1800 kg/m^3. The densities of the constituents were 1850 kg/m^3 for the masonry rubble and 640 kg/m^3 for the autoclaved aerated concrete [29].

The thermal process and the type, content and fineness of the expanding agent are decisive for converting the green granules into expanded granules with defined properties. For the thermal treatment, sufficient gas formation induced by the expanding agent in a temperature range in which sufficient amounts of melting phases are already present are an absolute requisite for the production of porous granules. At the same time, however, a collapsing of the granules due to an excessive amount of melting phase must be avoided. Fig. 10 illustrates the correlations:

- The diagram on the left shows that the temperature ranges should lay between 1260 and 1290 °C. Insufficient firing temperature (<1260 °C) prevents complete decomposition of the SiC and the amount of melting phase that is formed is not sufficient. At excessive temperatures, the granules will shrink; the density increases.
- In respect of the amount and the fineness of the expanding agent there is also an optimum. When low amounts are added, or a relative to the matrix material coarser additive is used, granules of high density are produced. When higher amounts have been added and in a finer preparation, pore formation increases, resulting in a lower density. The addition of too high amounts causes the granules to collapse. The density increases once again.

In Fig. 11, the formation of polyedric pores in granules manufactured with different amount of expanding agent is shown. Lightweight granules with density of 0.62 g/cm^3 are produced when 3% expanding agent has been added. Dense granules result when no expanding agent whatsoever is added. Accordingly, the granules can be adjusted to suit a given application by appropriately dosing the porosity enhancer.

After the laboratory investigations were completed, lightweight aggregate in the amount of approx. 150 kg

Table 5
Properties of the lightweight aggregates manufactured in the pilot plant

Bulk density classes (kg/m^3)	Yield (in the different density classes) (%)	Water adsorption (%)	Particle strength (N)
400–500	18.2	5	103
500–600	51.8	4	159
600–700	20.9	4	173
700–800	9.0	3	251

Table 6
Properties of concretes made with different lightweight aggregates

Lightweight aggregate type	Compressive strength[a] (N/mm^2)	Concrete density (kg/m^3)	Resistance to freeze-thaw cycle		Thermal conductivity (W/mK)
			Mass loss per surface (g/m^2)	Change of E_{dyn} (%)	
Expanded clays	6.5	871	285	−67.9	0.24
Granulate	12.5	1120	169	−2.6	0.35

[a] 150 mm Cube, after 7 days.

Fig. 12. Production of precast concrete blocs from masonry lightweight aggregates.

was manufactured to pilot plant scale. The used mixture consisted of masonry powder <100 μm (49.5%), autoclaved aerated concrete powder <100 μm (49.5%) and SiC powder <30 μm (1%). The particle size of the green granules ranged between 4 and 5.6 mm. The burned granules produced in the rotary kiln at a temperature of 1230 °C have a particle size from 5.6 to 8 mm. The bulk density ranged from 400 kg/m^3 to 800 kg/m^3, with the classification into bulk density classes shown in Table 5. Water adsorption at 3–5% was very low, compared to the granules manufactured in the laboratory.

The aggregates were tested for such properties as freeze-thaw resistance and thermal conductivity. First results on their fitness in practice were obtained in test performed with lightweight concrete blocks in a precast concrete plant. Of the aggregates used in that plant – expanded slate 0/4 mm and expanded clay 4/8 mm – the expanded clay was volumetrically replaced with lightweight aggregates from masonry and autoclaved aerated concrete sand. The properties of both types of concrete are compared in Table 6. The manufactured blocks are shown in Fig. 12.

The results confirm that concrete made with the lightweight aggregates presented in this paper are quite competitive with, for example, expanded clay, which has already established itself in the market place. With an optimized mix design, further improvements of the properties should be achievable.

5. Conclusion

The investigations performed in the laboratory and in the pilot plant have demonstrated that the variety of constituents suitable for lightweight aggregate production can be broadened. Suitable are zeolitic rocks, of which there are deposits in many regions of Russia. In Germany, masonry rubble could be used as alternative raw material. The technological process for the manufacture of the granules is similar for both materials. Grinding is followed by shapening by means of granulation. Subsequently, the green granules are burned at temperatures of about 850 °C for zeolitic constituents and at around 1230 °C for masonry rubble. The bulk density of the aggregates made from zeolitic rock lies between 420 and 480 kg/m^3. The densities of the lightweight aggregate from masonry rubble can be adjusted in a range from 530 to 1800 kg/m^3, as required. With the application of the findings and experiences gained in the two research facilities it should be possible to further enhance the process and the products for both variants.

In recycling construction and demolition wastes, the strict dependency of the product quality on the quality of the constituent material is often typical. For the utilization process for masonry rubble described here, this dependency is clearly reduced, if not altogether eliminated: of a fine-grained mixed material of fluctuating quality, a homogeneous product of defined particle size and composition is manufactured.

Acknowledgements

Research focusing on the use of zeolitic rock in the production of lightweight aggregates is conducted within the framework of the Russian federal scientific and technical program “Research and elaboration in the priority directions of development of science and techniques”, Grant 2006 -RI-111.0/002/018. The authors gratefully acknowledge the help of the colleagues at the Bauhaus-University Weimar in the course of the analyses.

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