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ORIGINAL ARTICLE

Development of thermo-mechanical treatment for recycling of used concrete

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Abstract Compared to virgin aggregates concrete recyclates have some specific properties because of the attached hardened cement paste. By the method of thermo-mechanical treatment, the hardened cement paste can be removed. In this paper systematic experiments are described. The aim was to understand the liberation process better. The product quality, the parameters of the process and the interaction were experimentally investigated. The results of the study show that with a low treatment temperature of 250–300 °C and a sufficient high duration of mechanical treatment recycled aggregates with properties similar to natural aggregates can be generated.

Keywords Thermal and mechanical treatment · Recycled aggregates · Hardened cement paste · Apparent density and water adsorption

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1 Introduction

Today, concrete is the most commonly used building material. About 20,000,000,000 tons of concrete are produced every year worldwide [1]. At the same time, large volumes of concrete rubbles are generated. Therefore, recycling of concrete rubble becomes increasingly important.

Recycled aggregates produced from concrete rubble by means of single- or multistage comminution in impact and/or jaw crushers are composites of hardened cement paste (HCP) and original aggregates. If these composites are used for the concrete production again, a concrete is formed which contains "old" HCP as constituent of the recycled aggregates (Fig. 1) and "new" HCP used to bond the aggregates together.

Because of its porosity and structure the HCP can cause a degeneration of the concrete produced of recycled aggregates. Especially the modulus of elasticity, the shrinkage and the creep are influenced strongly by the HCP [2]. Therefore, today the reuse of the processed concrete rubble is mainly restricted to fill material, material for sub-grade improvement and material for base courses in road construction. High-quality recycling of aggregates from demolished concrete being used as aggregate in new concrete has only been realized to a limited extent so far, although relevant technical regulations are available. According to a survey of a working group of the German trade and industry associations involved in the construction sector only 4.9 % of the total amount

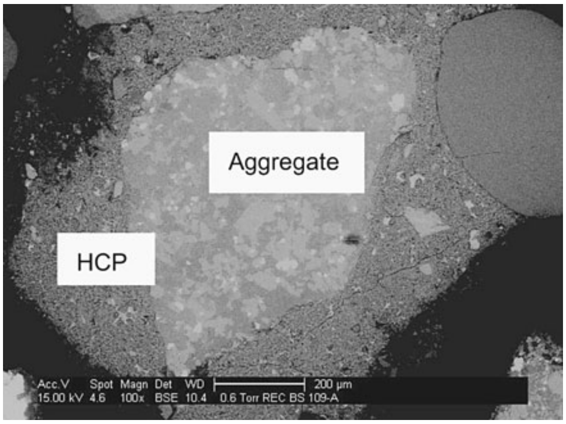

Fig. 1 Layer of HCP at the surface of an aggregate grain (from [2])

of 49.6 million *t* of recycling building materials produced in 2004 in Germany was used as concrete aggregates [3].

One way to improve the quality of the concrete aggregates is to remove the HCP. In the literature various methods are described that are developed to liberate the original aggregate from the concrete rubble. Examples for such methods are

– mechanical treatment by abrasion,
– combination of a thermal and a mechanical treatment or
– electrodynamic or electrohydraulic treatment.

The methods for the removal of HCP from concrete rubble by means of a combined thermal and mechanical treatment were developed in Japan and in the Netherlands [4, 5]. In both processes, the HCP is stressed by the thermal treatment at first. In the process developed in Japan, air preheated to 300 °C flows through the concrete rubble. No information is given about the temperature reached by the concrete itself. After the thermal treatment, the concrete is subject to abrasion stress in two ball mills—one mill for the coarse fractions, the other for the fine fractions. The process is currently tested at a technical scale with a throughput of 5 *t*/h [6]. In the process developed in the Netherlands, the concrete rubble is heated to a temperature of 700 °C in a rotary kiln. It is not subject to any additional abrasive stress. The separation between the coarse fractions, the sand and the HCP rich powder is carried out with screens and an air classifier.

Alternative methods for the removal of HCP from concrete rubble use high-performance sonic impulses as a tool for comminution and liberation [7–9]. By variations of the electrical parameters, the converted energy can be varied widely. The results published by Linsz et al. [8] show that the number of impulses and the voltage are the main factors influencing the obtained particle size reduction and the quality of crushing products. After the treatment, up to 60 % of the particles with a particle size >2 mm are HCP free.

2 Experimental procedures

2.1 Materials and methods

The objective of the experiments described in this paper is to figure out the effects of the main process parameters of the thermal and the mechanical treatment on the quality of recycled aggregates [10]. The experiments focused on the following parameters:

Focus 1: Liberation behavior of the concrete divided in particle size classes in dependence on the temperature of the thermal treatment.

Focus 2: Liberation behavior of the concrete in dependence on the parameters of the mechanical treatment, especially the duration.

Focus 3: Interactions between the thermal and mechanical treatment and the liberation behavior of the concrete.

For the experiments, only laboratory concretes were used. They contained sands and gravels, sands and chippings, respectively, as aggregate. The strength classes were B25, B35 and B45.

The procedure of the experiments is shown in Fig. 2. The fractions 2/4, 4/8 and 8/16 mm of the crushed concretes were treated for 30 min separately for each fraction in a laboratory furnace at temperatures that varied between 100 and 600 °C. Mechanical treatment was performed in a ball mill or a laboratory-scale planetary mill depending on the volume to be treated. For the focus 1 a constant milling time of 3 min was maintained. For focus 2, the thermal treatment of the fraction 8/16 mm was performed at 500 °C while the milling time was varied. For focus 3 the thermal treatment varied between 100 and 600 °C and the grinding duration varied between 3 and 14 min.

After the treatment the material was screened in the same fractions as the input material. For each fraction a fine product with particle sizes lower than the

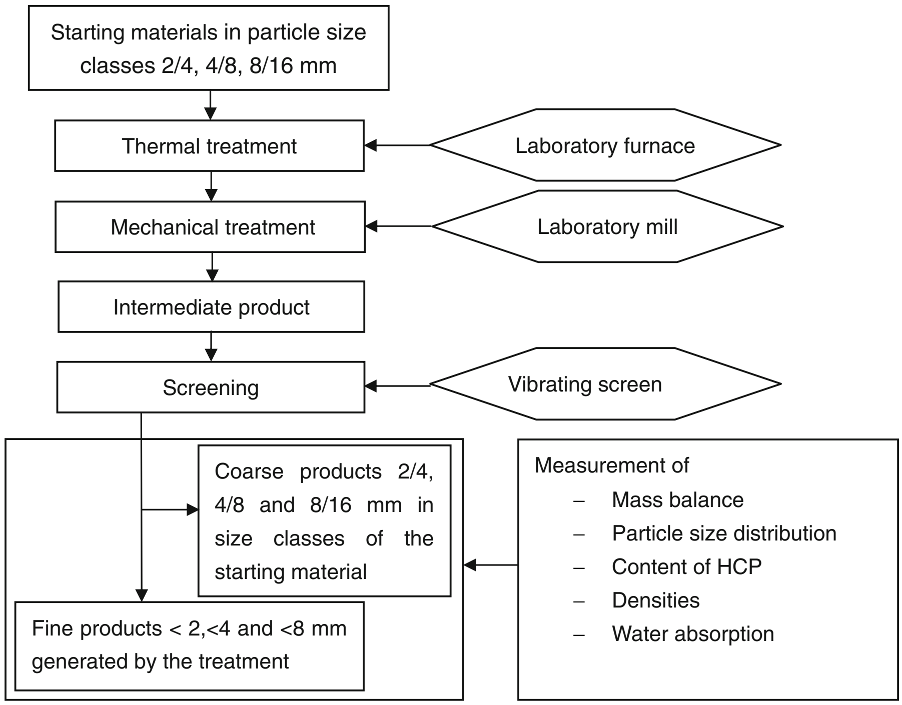

Fig. 2 Procedure of the experiments

minimum size of the input fraction was produced. The masses and the particle size distribution of the remaining coarse fractions as well as the generated fine fractions were measured. The coarse fractions and the fine fractions were examined with regard to the content of HCP, the density and the water adsorption. In some cases further properties as the particle shape or the specific surface area are measured. From the measured data different parameters for the evaluation of the process and the products were calculated.

The process is described by the size reduction ratio and the yield of the remaining coarse fractions as the considered products. The quality of the products is characterized by the content of HCP, the apparent density and the water absorption. Additionally the HCP content of the fraction <0,125 mm was measured. In Table 1 the parameters for the evaluation of the process and the products are summarized.

2.2 Results

2.2.1 Size reduction ratio and yield of coarse products

The particles of the concrete are reduced in their size by the thermal treatment. The size reduction ratio as quotient of the mean particle sizes of the input material and the mean particle sizes of the treated material is between 1.18 and 2.19. Compared with crushing processes in jaw crushers that result in size reduction ratios >10 the effect of the "thermal" comminution is rather low.

The temperature of the treatment and the particle size of the starting material have key influences on the yield after the thermal treatment (Fig. 3). As shown in the figure for the small particles 2/4 mm the amount of the input fraction that remains after the treatment is nearly constant. For the coarser fractions the yield decreases with increasing temperature. The decrease depends on the particle size. It is higher for the tested coarsest fraction 8/16 mm than for the fraction 4/8 mm. The humidity of the samples and the cooling rate have no influence on the yield.

Due to the mechanical treatment the size reduction ratio is between 1.84 and 2.35. The yield is influenced by the residence time of the material in the ball mill (Fig. 4). At 25 min the yield of the coarse product 8/16 mm reaches a value of about 0.3 kg/kg and remains constant with further milling up to 40 min. The particle size of the input material has only a minor influence on the yield.

Table 1 Parameters for the evaluation of the process and the products

Characteristic values	Equations	Explanation of typical cases
Size reduction ratio R_m	$R_m = \frac{X_{m,S}}{X_{m,p}}$ (–) $X_{m,s}$ is the mean grain size of the starting material in mm; $X_{m,p}$ is the mean grain size of the product in mm	$R_m = 1$ for the coarse material: No comminution has taken place. The larger the R_m, the stronger the comminution by the thermal or the thermal–mechanical treatment
Yield related to the coarse product a_G	$a_G = \frac{m_{cp}}{m_s}$ (–) m_{cp} is mass of the coarse product in kg; m_s is Mass of the starting material in kg	$a_G = 0$: The feed material has been completely processed to fine material. The smaller a_G the stronger the comminution by the thermal or the thermo-mechanical treatment
HCP content in the products Z_{cp}, Z_{fp}	$Z_{cp} = \frac{m_{cp}}{m_t} \times 100$ (%) m_{cp} is mass of HCP in a sample of the product in kg; m_t is the total mass of the sample of the product in kg	$Z_{cp} = 0$ %: Coarse products without HCP, very good quality. $Z_{fp} = 100$ %: Powder faction consists only of HCP
Absolute density $\rho_{Absolute}$ apparent density $\rho_{Apparent}$	$\rho_{Absolute} = \frac{m}{V_{Pore-free}}$ (g/cm^3) $\rho_{Apparent} = \frac{m}{V_{porous}}$ (g/cm^3) m is the mass of the composite in g; $V_{pore\text{-}free}$ is volume of the composite without pores in cm^3; V_{porous} is the volume of the composite with pores in cm^3	$\rho_{Abs,cp} = \rho_{Abs,\ virgin\ aggregate}$ $\rho_{App,cp} = \rho_{App,\ virgin\ aggregate}$ Coarse products without HCP, very good quality
Water absorption after 24 h W_{24h}	$W_{24h} = \frac{m_1 - m_3}{m_3} \times 100$ (%) m_1 is the mass of the material with absorbed water in kg; m_3 is the mass of the dry material in kg	W_{24h} <1 %: The 24 h-water absorption tends to the value of virgin aggregates

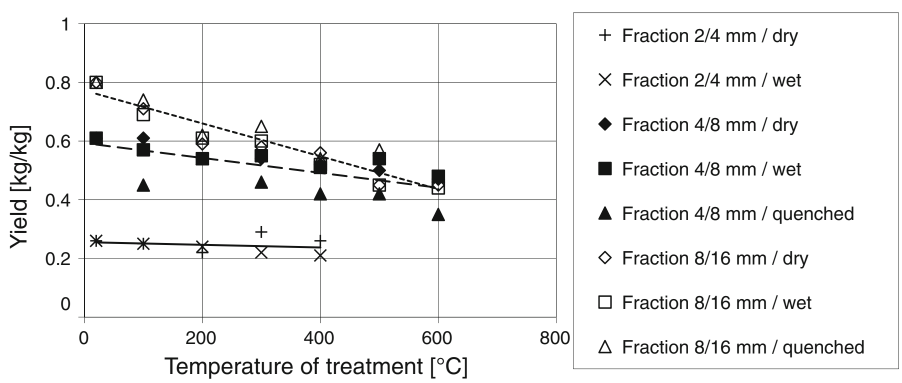

Fig. 3 Influence of the temperature and the particle size of the starting material on the yield of the thermal treatment

If the thermal and the mechanical treatment will be combined (Fig. 5) it can be recognized that the influence of the milling time is similar for a treatment at ambient or low temperatures compared with a treatment at the highest tested temperature of 600 °C. For example, the same yield of 0.55 kg/kg is achieved if a milling time of 14 min and no thermal treatment is realized or a time of 1 min and a treatment at 600 °C is chosen. Between these both extremes the range of 200–300 °C is most interesting. At this rather low temperature the same yield like at a temperature of 600 °C can be achieved if the milling time is extended from 1 to 8 min.

2.2.2 *Quality of coarse products*

The objective of the thermal–mechanical treatment is to produce a high-quality aggregate from the old concrete. The HCP content of the coarse products decreases with the increase of the temperature of thermal treatment (Fig. 6). Additionally it is influenced by the duration of the mechanical treatment (Fig. 7). From the results it

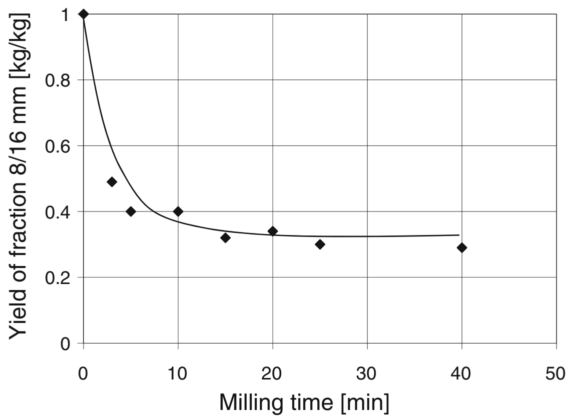

Fig. 4 Influence of the duration of grinding on the yield of the mechanical treatment

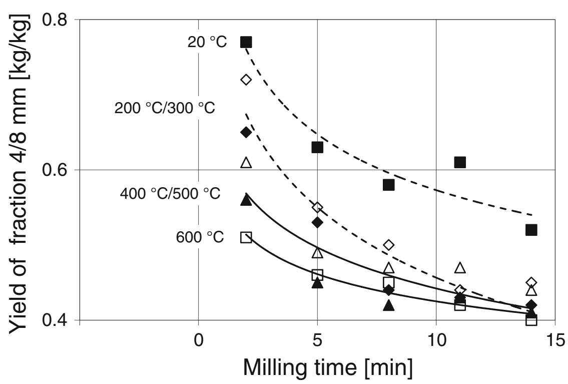

Fig. 5 Influence of the duration of grinding and temperature on the yield

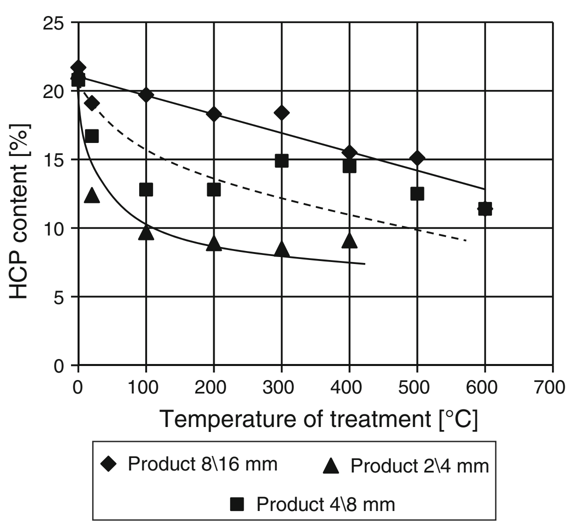

Fig. 6 HCP content of the coarse products generated by thermal treatment (0 °C means: no treatment)

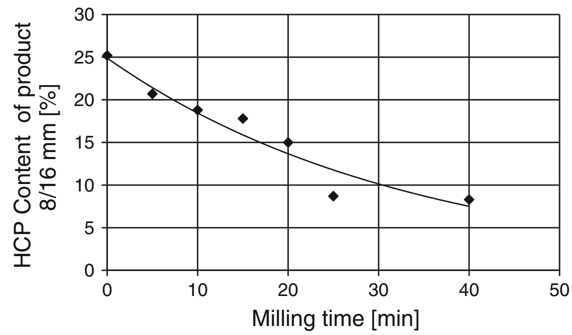

Fig. 7 HCP content of the coarse products generated by mechanical treatment

becomes clear that the HCP content of the coarse products is influenced by the particle size of the starting material. The HCP content of the products generated from 8/16 mm fraction as starting material is higher than the content of the products generated from 2/4 mm fraction as starting material.

The quality of the coarse products of the starting material fractions is improved after the thermal treatment or the mechanical treatment. The apparent density of the coarse fractions is mostly increased most with the first grinding. Further treatment results in smaller effects (Tables 2, 3). After thermal treatment at 400 °C or mechanical treatment for 25 min the apparent density of the coarse products already reaches the value of the original aggregate.

The water absorption of the coarse products after 24 h decreases after the thermal or mechanical treatment (Tables 4, 5). Especially after the mechanical treatment for 40 min the water absorption of the product 8/16 mm is 1.1 %, i.e., near to the value of the original aggregate.

The quality of the concrete rubble is clearly improved by the thermal–mechanical treatment according to the result of the experiments. In Figs. 8 and 9 it is shown, that the apparent density as well as the water absorption strongly depends on the HCP content. HCP content is key parameter for the quality. In the German standard the HCP content is taken into consideration by a limit of apparent density that must be fulfilled. With 2.0 g/cm^3 the limit is rather low.

2.2.3 *Quality of fine products*

In the experiments the HCP can be removed into the fine products. In the best case, the HCP becomes very

Table 2 Apparent density (g/cm^3) of the coarse products after the thermal treatment

Temperature of treatment (°C)	No treatment	20	100	200	300	400	500	600
Product 2/4 mm	2.38	2.53	2.57	2.57	2.58	2.58	–	–
Product 4/8 mm	2.45	2.54	2.56	2.56	2.57	2.56	2.58	2.59
Product 8/16 mm	2.55	2.65	2.62	2.65	2.65	2.67	2.68	2.74

Table 3 Apparent density (g/cm^3) of the coarse products after the mechanical treatment

Milling time (min)	No treatment	5	10	15	20	25	40
Product 8/16 mm	2.32	2.52	2.53	2.52	2.55	2.60	2.60

Table 4 24 h-water absorption (%) of the coarse products after thermal treatment

Temperature of treatment (°C)	20	100	200	300	400	500	600
Product 2/4 mm	3.8	2.8	2.9	2.6	2.4	–	–
Product 4/8 mm	4.7	4.3	3.6	3.5	2.9	2.5	2.3
Product 8/16 mm	4.3	3.8	3.7	3.4	2.8	2.2	1.9

Table 5 24 h-water absorption (%) of the coarse products after mechanical treatment

Milling time (min)	No treatment	5	10	15	20	25	40
Product 8/16 mm	5.7	3.0	2.3	1.8	1.9	1.6	1.1

fine by the thermal and mechanical treatment and is enriched in the powder fraction.

In the presented experiments, the generated fine fraction 0/0.125 mm is the finest product. After the thermal and the mechanical treatment, the HCP content in the fraction 0/0.125 mm reaches a maximum value of 60 %. At the constant mechanical treatment of 3 min milling time, the HCP content in the fraction 0/0.125 mm first increases and then decreases with the increase of the temperature. The temperatures for the maximum HCP content in the fraction 0/0.125 mm depend on the particle size of the input material. For the fraction 2/4, 4/8 and 8/16 mm the temperatures are 306, 380 and 460 °C, respectively. At the same mechanical treatment procedure higher temperatures are necessary to produce a HCP-rich powder from the coarse fractions compared with the sand fraction (Fig. 10). It can be assumed, that caused by the heat transport the coarser particles need a higher treatment temperature than the finer particles to get the same medium particle temperatures.

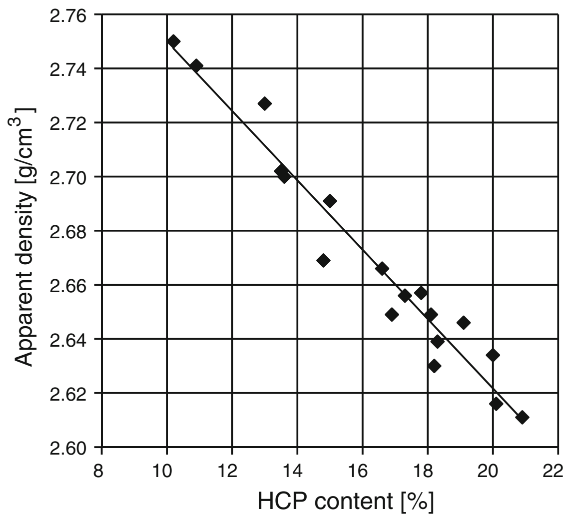

Fig. 8 Apparent density in dependence on the HCP content of the coarse products

At a constant temperature of 500 °C the HCP content in the fraction 0/0.125 mm decreases with the extension of the milling time (Fig. 11). That means, with the extension of the milling time the coarse particles can be grinded especially at the corners or the edges.

2.2.4 Influence of the milling parameters on the liberation of the concrete rubble

Besides the milling time the milling parameters have an influence on the liberation of the concrete from HCP too. The results of the experiments are summarized in Table 6.

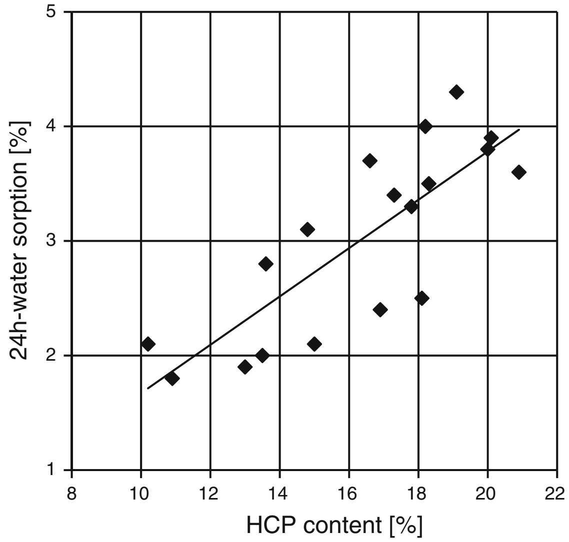

Fig. 9 Water adsorption in dependence on the HCP content of the coarse products

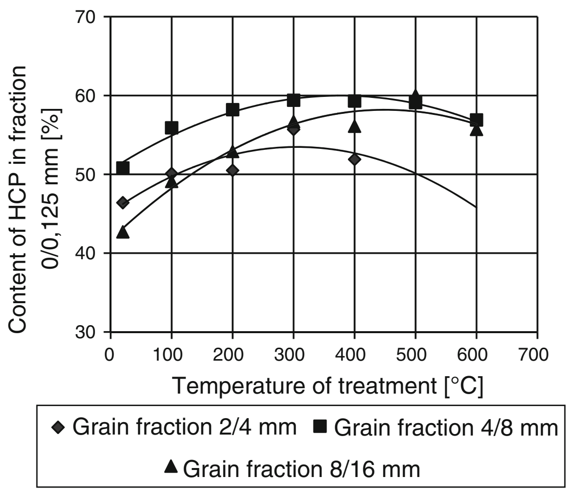

Fig. 10 Influence of thermal treatment temperature on the content of HCP in the product 0/0.125 mm

2.2.5 *Combination of the thermal and mechanical treatment for the recycling of concrete*

The results of the experiments show that the treatment temperature and milling time mutually influence each other with regard to the comminution of the starting material and improvement of the quality of the coarse products by the thermo-mechanical treatment (Fig. 12). In the appropriate temperature range, the quality of the starting material can be selectively

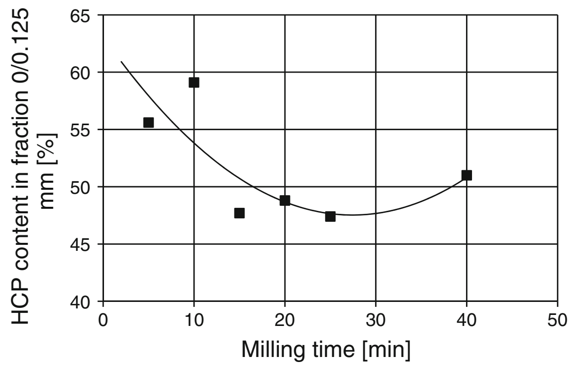

Fig. 11 Influence of the duration of the mechanical treatment on the content of HCP in the product 0/0.125 mm

Table 6 Influence of the milling parameters on recycling of the used concrete

Milling parameter	Influence on recycling of used concrete
Increase of the revolve speed	Increase of the size reduction ratio
	Considerable improvement of the quality of the coarse products
Increase of the mill feed filling	Low influence
Increase of the grinding media size	Increase of the size reduction ratio
	Improvement of the quality of the coarse products
	Adverse effects for the comminution of the fine starting material
Increase of the grinding media density	Improvement of the quality of the coarse products like the influence of the grinding media size

adjusted by varying the treatment temperature and milling time. The apparent density of the product from a input material 4/8 mm depends, with a short milling time (2, 5 min), to a large extent on the treatment temperatures. Only at high treatment temperatures the required apparent densities are achieved. On the other hand, with longer milling time (8, 11 min), the increase of the apparent density is lower with increasing temperature. Already at treatment temperatures of around 300 °C, apparent densities are achieved close to the apparent density of the input material.

With the combination of milling time and temperature, a certain apparent density of the coarse products can be achieved (Fig. 13). For example, the same

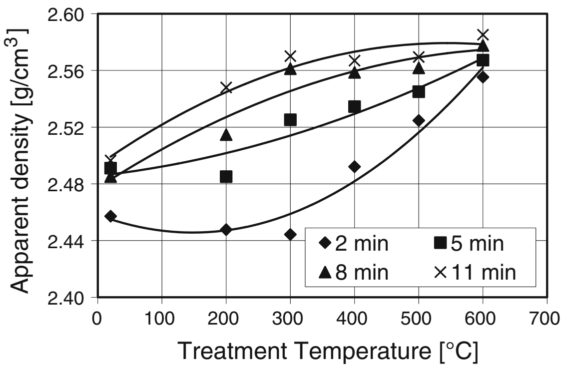

Fig. 12 Influence of the treatment temperature and milling time on the apparent density of the coarse product (starting material 4/8 mm)

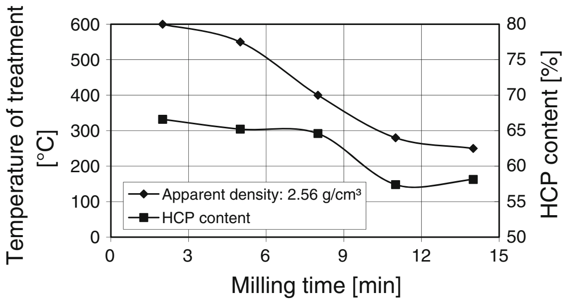

Fig. 13 Combination of the milling time and the temperature for production the coarse products (input material 4/8 mm)

apparent density of 2.56 g/cm^3 can be obtained with a temperature of 600 °C and a 2 min milling time or with a temperature of 250 °C and a 14 min milling time. With regard to the enrichment of the HCP in the powder fraction 0/0.125 mm considerable differences appear between these both treatment regimes. The higher the milling time the lower the HCP content, caused by the increasing abrasion of the treated particle.

3 Final remarks

The liberation of crushed concrete is necessary when high-quality hardened cement-paste-free aggregates have to be produced, which allow reuse in concrete without any restrictions. Such liberation can be achieved with a combination of thermal treatment, followed by mechanical treatment. It was empirically proven that even moderate temperatures of 250–300 °C are sufficient to remove the hardened cement paste, if the following mechanical treatment is intensive enough. By this method coarse aggregates can be produced with an apparent density near that of virgin aggregates. As a by-product a considerable quantity of powder 0/0.125 mm is generated in which the cement paste is enriched to amounts of about 55 %.

Alternatively the thermal treatment can be performed at temperatures of 500 °C followed by a short mechanical treatment. Then the quantity of powder 0/0.125 mm is lower and its content of cement paste is higher.

The decision for one of the both possibilities depends from practical reasons. If waste heat with the needed temperature of 250–300 °C is available for instance, then the first variant should be realized. If it is more important to have opportunities for the reuse of the cleaned coarse fraction as well as the cement paste enriched powder, then the second variant should be chosen. According to the experimental results reported in [11, 12], it seems to be possible to transform the powder to a hydraulic binder.

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