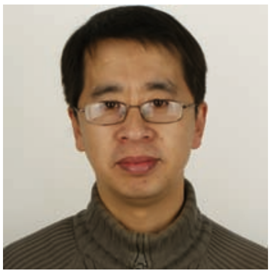

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Thermo-mechanical treatment

Study of the factors influencing thermo-mechanical treatment for recycling used concrete

Summary: The liberation process developed is intended to improve the quality of concrete recyclates for the production of fresh concrete. For this end, thermal and mechanical treatment is combined. It was empirically proven that even moderate temperatures of around 300 °C are sufficient to make the hardened cement paste (HCP) brittle, so it can then be removed by means of mechanical treatment. The products of this process are aggregates with properties close to those of natural aggregates as well as a fine-grained material high in hardened cement paste that can be further processed to a binder.

1 Introduction

Concrete is the most commonly used building material in our time. Around 8000 mill. t concrete are produced annually worldwide [1], including around 250 mill. t in Germany [2] and around 3000 mill. t in China [1]. At the same time, large volumes of concrete rubble are produced. The forecast for Germany, which is based on the concrete volumes produced and assumptions regarding the lifetime of concrete structures, indicates that around. 100 mill. t of concrete rubble could be produced by the year 2020 [3]. The volumes of concrete rubble expected in China range between 200 and 1040 million t/a [4]. They are in a similar range as the volumes of concrete produced, and about 10 times higher than the volumes specified for Germany.

At present, the recycling of the processed concrete rubble is mainly restricted to filler material and material for base and anti-freeze courses. High-quality recycling of concrete, with recyclate being used as aggregate in fresh concrete, has so far only been realized to a limited extent, although the requirements and applications are clearly defined by relevant regulations. According to the survey conducted by the Arbeitsgemeinschaft Kreislaufwirtschaftsträger Bau (a working group of the German trade and industry associations involved in the construction sector), only 4.9 % of a total of 49.6 million t of RC building materials produced in 2004 was used as concrete aggregate [5].

Demolition of buildings in China

2 Current the treatment processes for the concrete liberation

Recycled aggregates produced by means of single- or multi-stage comminution in impact and/or jaw crushers from concrete rubble are composites of hardened cement paste (HCP) and the original aggregates. If these composites are reused for concrete production, a concrete is formed which contains "old" HCP in addition to the aggregate and the "new" HCP used to bond everything together. This can effect deterioration of the hard concrete properties, especially the modulus of elasticity, shrinkage and creep, which are influenced particularly strongly by the HCP. This chain of effect was confirmed in empirical studies [6]. At the same time, it follows that the effects of recycled aggregate on the concrete properties can vary depending on how much HCP the recyclates contain.

In the literature various processes are described that are designed to liberate the concrete, i.e. break down the concrete into the original aggregate and HCP. These processes are based on

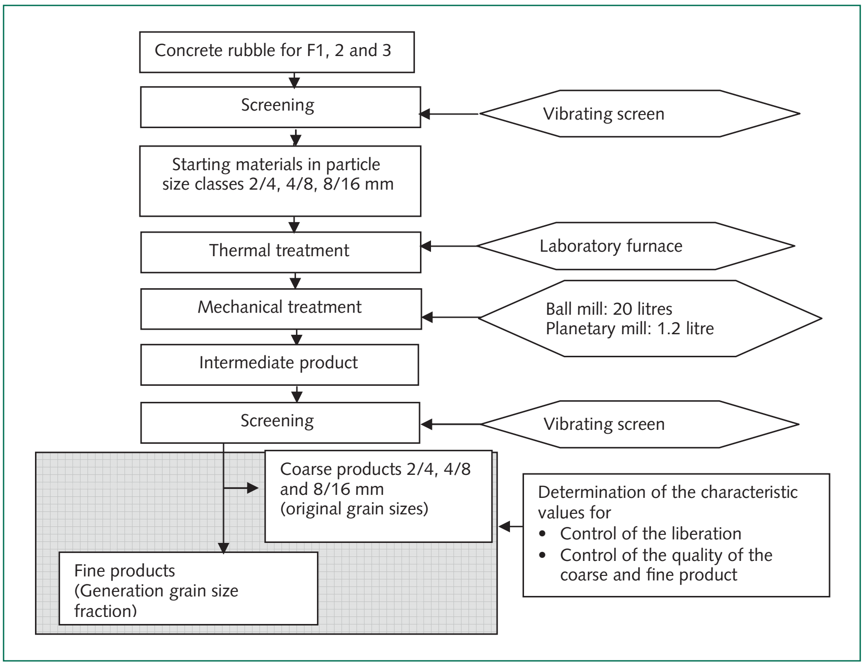
- mechanical treatment,
- thermo-mechanical treatment or
- electrodynamic or electrohydraulic treatment.

The processes in which the HCP is removed from used concrete rubble by means of thermal treatment were developed in Japan and the Netherlands. In both processes, the thermal treatment is applied to soften the HCP. In the Japanese process, air preheated to 300 °C flows through the concrete rubble. No specifications are given as regards the temperature reached by the concrete itself. After this thermal treatment, the concrete is subjected to abrasion stresses in ball mills. The process is currently under tests with a throughput of 5 t/h [7]. In the Dutch process, the concrete rubble is heated to a temperature of 700 °C in a rotary tube furnace. It is not subjected to any additional abrasive stress [8]. In the cited research, therefore, different treatment temperatures were regarded as necessary. According to these examples, it is possible to compensate for the lower treatment temperature with mechanical stress.

3 Empirical studies of thermo-mechanical treatment for used concrete recycling

3.1 Test focuses, starting materials and test procedure

Thermo-mechanical treatment is an expedient method for recycling used concrete, but the process is very complex and energy-intensive. A reduction of the thermal treatment temperature and the use of simply designed equipment could



1 Flow sheet showing the test procedure (SP: Focus)

contribute to improving the suitability of this method for field application.
Studies of the factors influencing thermal and mechanical treatment for recycling used concrete were focussed as follows:

- Focus 1: Liberation behaviour of used concrete on variation of the thermal treatment with constant mechanical treatment.
- Focus 2: Liberation behaviour of used concrete on variation of the mechanical treatment with constant thermal treatment.
- Focus 3: Interaction and combined effect of thermal and mechanical treatment on the liberation behaviour of used concrete.

For the studies, only laboratory concretes are used. Some of the concretes were already available in comminuted form as concrete rubble, in some cases concrete cubes first had to be prepared in laboratory jaw crushers. For Focuses 1 and 3 mixed laboratory concretes in the strength classes B25, B35 and B45 were available. They contained sands and gravel and sands and chippings (8/16 mm) respectively as aggregate. The model concrete for Focus 2 corresponds to the strength class B45 and contains sand and gravel (16/32 mm) as aggregate.

The test procedure is shown in **Fig. 1**. The crushed used concretes were first sized into the fractions 2/4, 4/8 and 8/16 mm on a vibrating screen. The resulting fractions were then treated in a laboratory furnace at temperatures varied between 100 and 600 °C for 30 min in each case. 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 study a constant milling time of 3 min was maintained. For Focus 2, thermal treatment was performed at 500 °C while the milling time was varied. After treatment, the intermediate product was sized into the original size range and resulting fines on a vibrating screen.

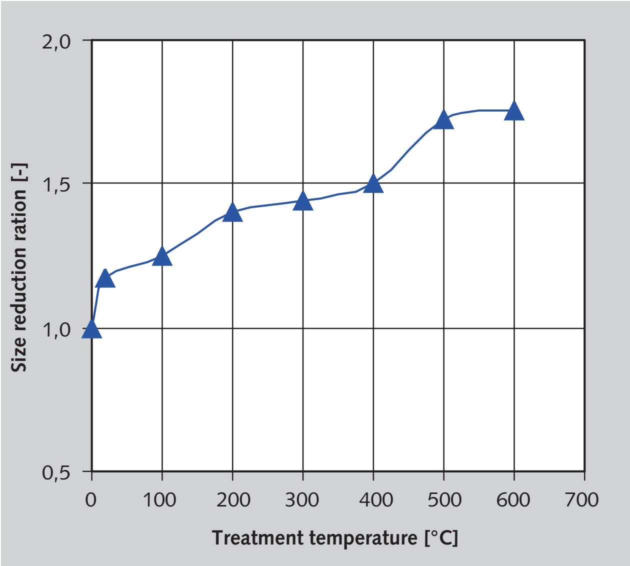
Evaluation of the effects achieved in the tests comprises two parts:

1. Process values for assessing comminution of the starting material – mass yield, size reduction ratio and residual content of the HCP in the coarse product.

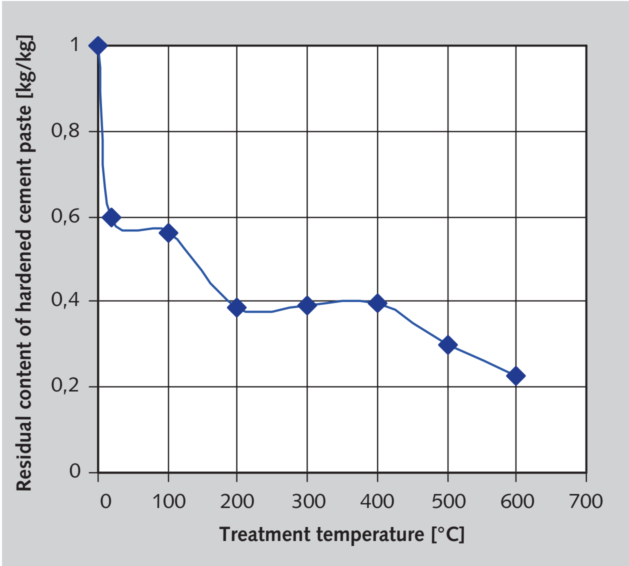
2. Characteristic values for evaluation of the quality of the products – density, HCP content, etc.

Table 1: Summary of the characteristic values for evaluation of the process

Effects to be proven and characteristic values	Equations	Explanation of the typical cases
Mass yield of coarse material a_G and fines a_F (m_A: mass of the starting material in kg; m_G: mass of the coarse material in kg; m_F: mass of the fine material in kg)	$a_G = \frac{m_G}{m_A}$ $a_F = \frac{m_F}{m_A}$ $a_G + a_F = 1$	$a_G = 0$, $a_F = 1$: The feed material has been completely processed to fine material. The stronger the comminution with the thermal or the thermo-mechanical treatment, the smaller is a_G
Size reduction ratio R_m: Ratio of the weighted mean grain size of starting material and products	$R_m = \frac{x_{m,A}}{x_{m,P}}$	$R_m = 1$ for the coarse material: No comminution has taken place. The stronger the comminution with the thermal or the thermo-mechanical treatment, the larger the R_m ratio
Residual content of hardened cement paste in the coarse material V_G and concentration of the hardened cement paste in the fines V_F ($Z_{S,A}$: mass of the hardened cement paste in the starting material in kg; $Z_{S,G}$: mass of the hardened cement paste in the coarse material in kg; $Z_{S,F}$: mass of the hardened cement paste in the fine material in kg)	$V_G = \frac{Z_{S,G}}{Z_{S,A}} \cdot \alpha_G$ $V_F = \frac{Z_{S,F}}{Z_{S,A}} \cdot \alpha_F$	$V_G = 0$ on account of $Z_G = 0$: No hardened cement paste remains in the coarse material. The stronger the concentration during thermal or thermo-mechanical treatment, the smaller V_G is



2 Starting material 8/16 mm – influence of the temperature of the thermal treatment on the size reduction ratio



3 Starting material 8/16 mm – influence of the temperature of the thermal treatment on the residual content of hardened cement paste in the coarse product

In Tables 1 and 2 definitions of the characteristic values used are summarized.

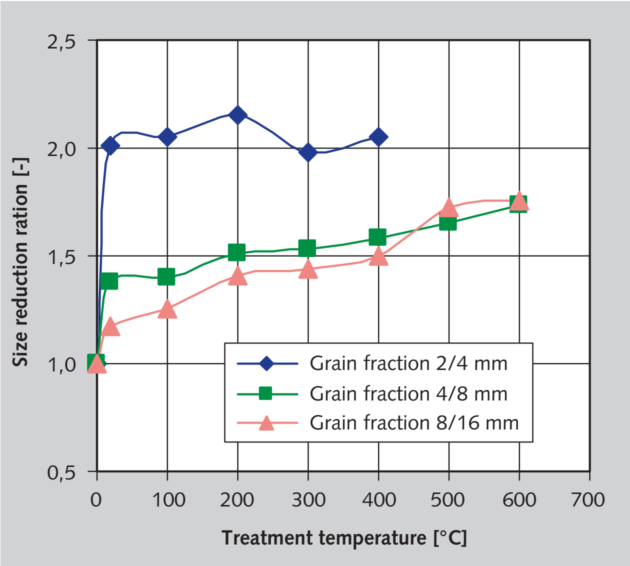
3.2 Key results

The temperature of the thermal treatment has a key influence on the result achieved – with a higher temperature, size reduction also increases. The size reduction ratio for the 8/16-mm starting material is 1.18, when the material is subjected to 3-minute mechanical treatment in the planetary mill without thermal treatment. It increases to 1.76 when the material is subjected to thermal treatment at 600 °C prior to milling (Fig. 2). Parallel to the comminution being intensified by tempering, the residual content of the hardened cement paste in the 8/16-mm coarse product decreases (Fig. 3).

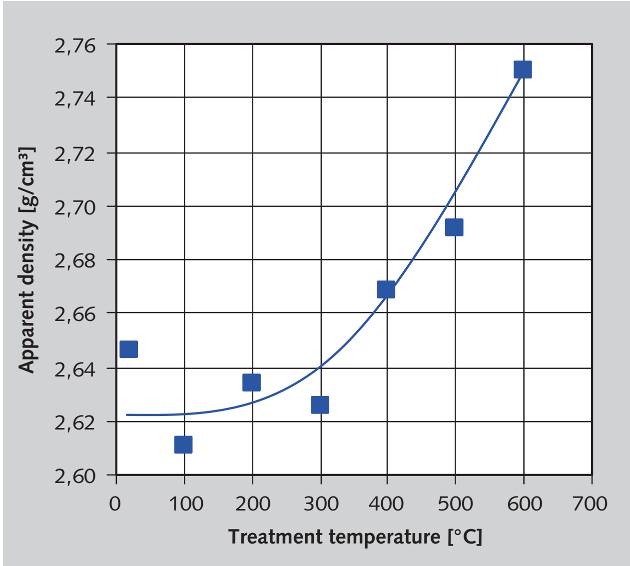
The effect of the thermal treatment is influenced by the particle size of the starting material. With constant mechanical treatment, for the coarse starting material, a stronger increase of the size reduction ratio could be determined with increasing treatment temperature. The higher the treatment

Table 2: Summary of the characteristic values for evaluation of the products

Effects to be proven and characteristic values	Equations	Explanation of the typical cases
HCP content and aggregate content of the coarse material $Z_{S,G}$, $Z_{A,G}$ HCP content and aggregate of the fine material $Z_{S,F}$, $Z_{A,F}$ ($Z_{S,A}$: Hardened cement paste content of the starting material)	$Z_{S,G} + Z_{A,G} = 1$	Ideal case: $Z_{S,G} = 0$ Coarse products without HCP particles sticking to it
		Partial separation: $0 < Z_{S,G} < Z_{S,A}$ Coarse products with HCP particles sticking to them
	$Z_{S,F} + Z_{A,F} = 1$	No separation: $Z_{S,G} = Z_{S,A}$ HCP content of the coarse products unchanged compared to the starting material
Theoretical and apparent density of the coarse material $\rho_{Theoretical,G}$, $\rho_{Apparent,G}$ ($\rho_{Theoretical,GK}$ und $\rho_{Apparent,GK}$: theoretical and apparent density of the aggregates; $\rho_{Theoretical,A}$, $\rho_{Apparent,A}$: theoretical and apparent density of the starting material)	$\rho_{Theoretical,G} = \frac{m}{V_{pore\text{-}free}}$	IIdeal case: $\rho_{Theoretical,G} = \rho_{Theoretical,GK}$ $\rho_{Apparent,G} = \rho_{Apparent,GK}$ Coarse products without HCP, very good quality
	$\rho_{Apparent,G} = \frac{m}{V_{porous}}$	No separation: $\rho_{Theoretical,G} = \rho_{Theoretical,A}$ $\rho_{Apparent,G} = \rho_{Apparent,A}$
Theoretical and apparent density of the fine material $\rho_{Theoretical,F}$, $\rho_{Apparent,F}$ ($\rho_{Theoretical,ZS}$, $\rho_{Apparent,ZS}$: theoretical and apparent density of the HCP)	$\rho_{Theoretical,F} = \frac{m}{V_{pore\text{-}free}}$	Ideal case: $\rho_{Theoretical,F} = \rho_{Theoretical,ZS}$ $\rho_{Apparent,F} = \rho_{Apparent,ZS}$ Fine products 0/0.125 mm without aggregate, very good quality
	$\rho_{Apparent,F} = \frac{m}{V_{porous}}$	No separation: $\rho_{Theoretical,F} = \rho_{Theoretical,A}$ $\rho_{Apparent,F} = \rho_{Apparent,A}$



4 Influence of the particle size of the starting material on the size reduction ratio during thermal treatment



5 Influence of the temperature of the thermal treatment on the apparent density of the coarse products

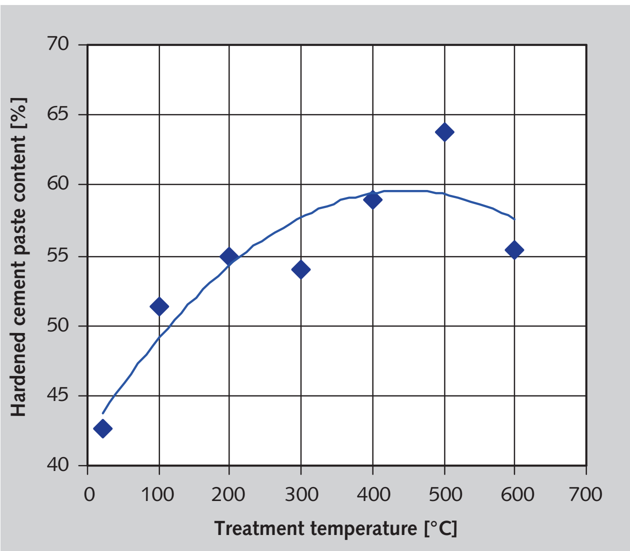
temperature is, the more effective is the comminution. For the fine starting material, even without thermal treatment, a effective comminution is achieved with the mechanical treatment, which does not progress further with temperature increase, but remains almost constant (**Fig. 4**).

The quality of the coarse products of the starting fractions is improved by thermal treatment. The apparent density of a 8/16-mm coarse product is increased by 4.2 % after thermal treatment at 20-600 °C (**Fig. 5**). The HCP removed from the coarse material by means of thermo-mechanical treatment is concentrated in the 0/0.125-mm fraction of the fine material. In the experiments, maximum HCP contents above 60 % could be achieved (**Fig. 6**).

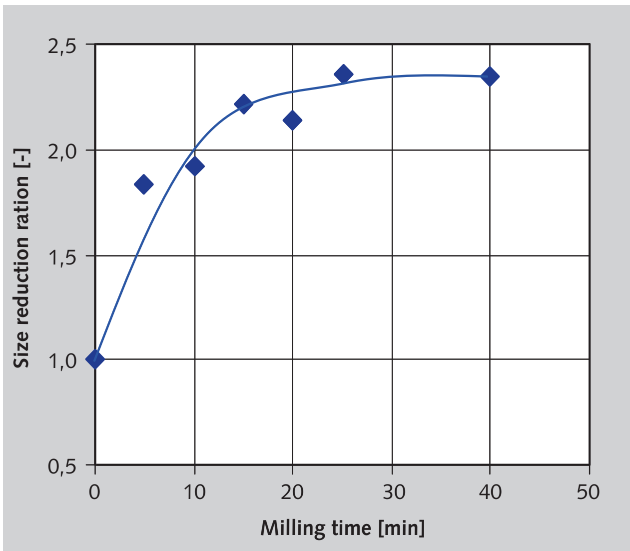
The duration of the mechanical treatment also influences the liberation of the concrete aggregate. Comminution of the starting material thermally treated at 500 °C increases with the lengthening of the milling time from 5-40 min (**Fig. 7**). At 25-40 min, the mass yield of the 8/16-mm coarse product reaches a value of around 0.3 kg/kg and remains constant with a further increase of the milling time to 40 min (**Fig. 8**).

Reduction of the HCP in the coarse material increases considerably with the milling time up to 25 min. Above 25 min, the increase is only slight (**Fig. 9**). The apparent densities of the 8/16-mm coarse products increase with the milling time (**Fig. 10**). The HCP can be increasingly separated from the aggregate with longer milling time.

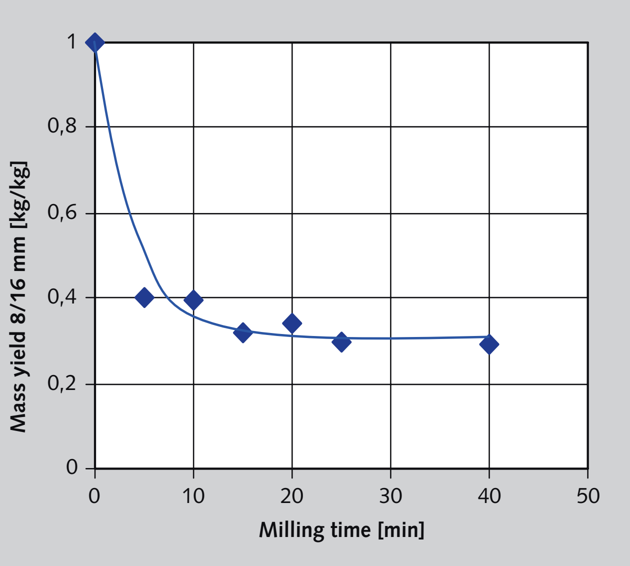
Besides the milling time, other milling parameters can also influence used concrete recycling based on thermo-mechanical treatment. A summary is shown in **Table 3**.



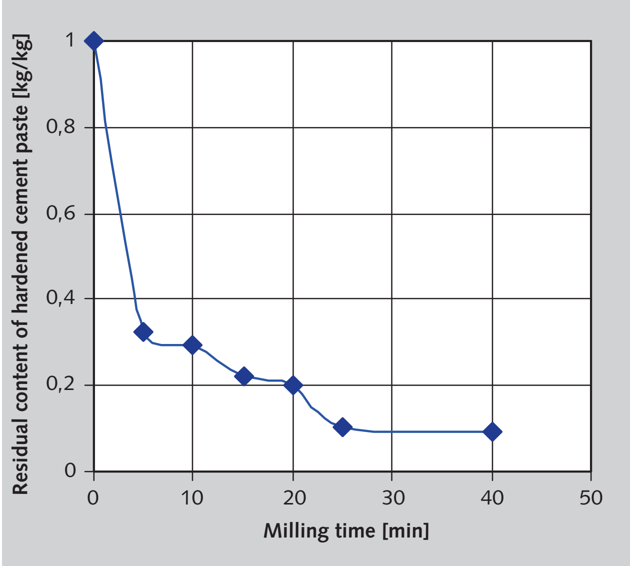
6 Influence of the temperature of the thermal treatment on the hardened cement paste content in the fine products



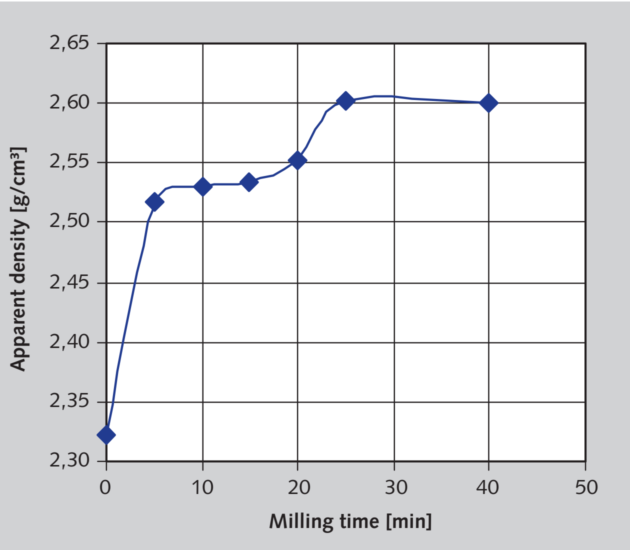
7 Influence of the milling time on the size reduction ratio of the coarse products



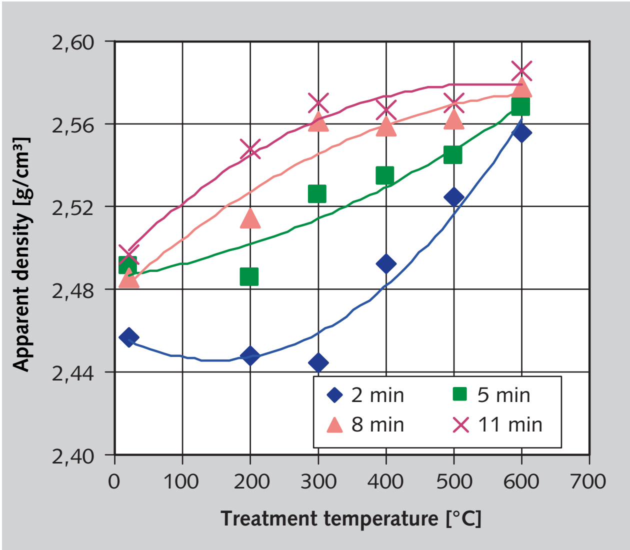
8 Influence of the milling time on the mass yield of the coarse products



9 Influence of the milling time on the residual content of the hardened cement paste in the coarse products



10 Influence of the milling time on the apparent density of the coarse products

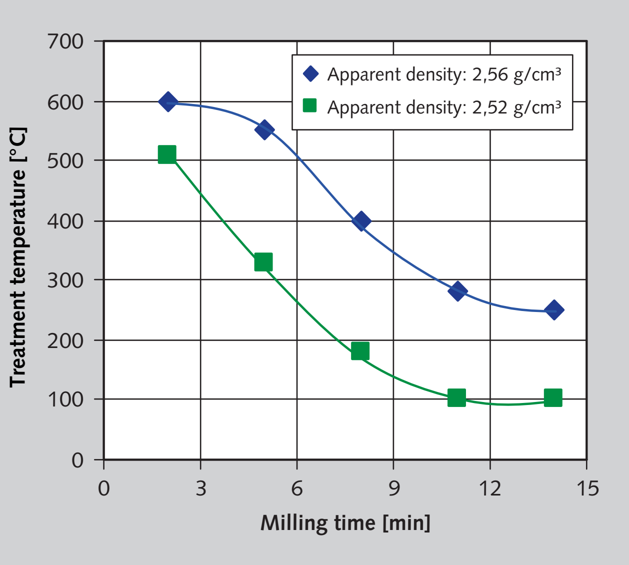


11 Starting material 4/8 – influences of the treatment temperature and the milling time on the apparent density of the coarse product

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 with thermomechanical treatment. In the appropriate temperature range, the quality of the starting material can be selectively adjusted by varying the treatment temperature and milling time. The apparent density of the 4/8-mm product depends, with a short milling time (2 min,

Table 3: Influence of the milling parameters on recycling of the used concrete with thermo-mechanical treatment

Milling parameter	Influence on recycling of the used concrete
Speed	Increase in the size reduction ratio and considerable improvement of the quality of the coarse product with increase in speed
Mill feed filling	Low influence
Grinding media filling	Higher grinding media filling is more favourable for used concrete recycling in the tested range from 0.21 to 0.30
Grinding media size	Increase in the size reduction ratio and improvement of the quality of the coarse product with increase in the grinding ball size. Adverse effects for the comminution of the fine starting material
Grinding media density	High grinding media density effects the improvement of the quality of the coarse product like the influence of the grinding media size



12 Starting material 4/8 – combination of the milling time and the temperature for the production of the coarse products

5 min), to a large extent on the treatment temperature. Only at high treatment temperatures are the required apparent densities achieved. On the other hand, with longer milling times (8 min, 11 min), the increase in the apparent density is lower with increasing temperature. Already at treatment temperatures of around 300 °C, apparent densities are achieved that are close to the apparent density of the starting material. With these milling times, temperature changes only have limited effect on the product quality (Fig. 11).

With the combination of milling time and temperature, a certain apparent density of the coarse products can be achieved. For example, the apparent density of 2.56 g/cm³ can be obtained with a temperature of 600 °C and a 2-minute milling time or also with a temperature of 280 °C and approx. 11 min milling (Fig. 12).

With regard to the HCP concentrated in the 0/0.125-mm fine grain, no complete balance between treatment temperature and milling time can be established, so with the combination 600 °C/2 min, a HCP content of 66.6 % results. It decreases to 58 % when thermal treatment is performed at 280 °C and the milling time is increased to 11 min. The reason is that with increased milling time, parallel to the HCP, the aggregate is comminuted too.

4 Final remarks

The liberation of the concrete is necessary when high-quality hardened cement-paste-free aggregates are to be produced, which permit reuse in concrete without any restrictions. Such material liberation can be achieved with a combination of thermal treatment, followed by mechanical treatment. It was empirically proven that even moderate temperatures around 300 °C are sufficient to make the hardened cement paste brittle so that this can be removed by means of mechanical treatment. The product are aggregates with properties that come close to those of natural aggregates in addition to fine grain with a high content of hardened cement paste.

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