Gefördert durch:

Bundesministerium für Wirtschaft und Energie

aufgrund eines Beschlusses des Deutschen Bundestages

Forschungsnetzwerk Mittelstand

Industrielle Gemeinschaftsforschung

Research association	VDZ Technology gGmbH
Research association 1:	VDZ Technology gGmbH Forschungsinstitut der Zementindustrie
IGF-Project-Nr.:	20656N
Period of approval:	01.06.2019 – 31.05.2021

Research topic:

Improvement of energy efficiency for the grinding of composite cements by means of separate ultra-fine grinding at semi-industrial scale

1 Initial situation

In recent years, the overall situation of cement production has changed significantly. The demand for cements with several main constituents has risen due to the requirements of modern building structures [VDZ 2020b]. At the same time a trend towards cements with a higher strength class can be identified (Figure 1) [VDZ 2019; Pal 2009]. Currently, CEM II- and, to a lesser extent, CEM III-cements benefit from this development, which is desirable for various reasons. For example, the clinker substitution rate for these cement-types allows a reduction in CO_2-emissions per tonne of cement and the preservation of valuable resources.

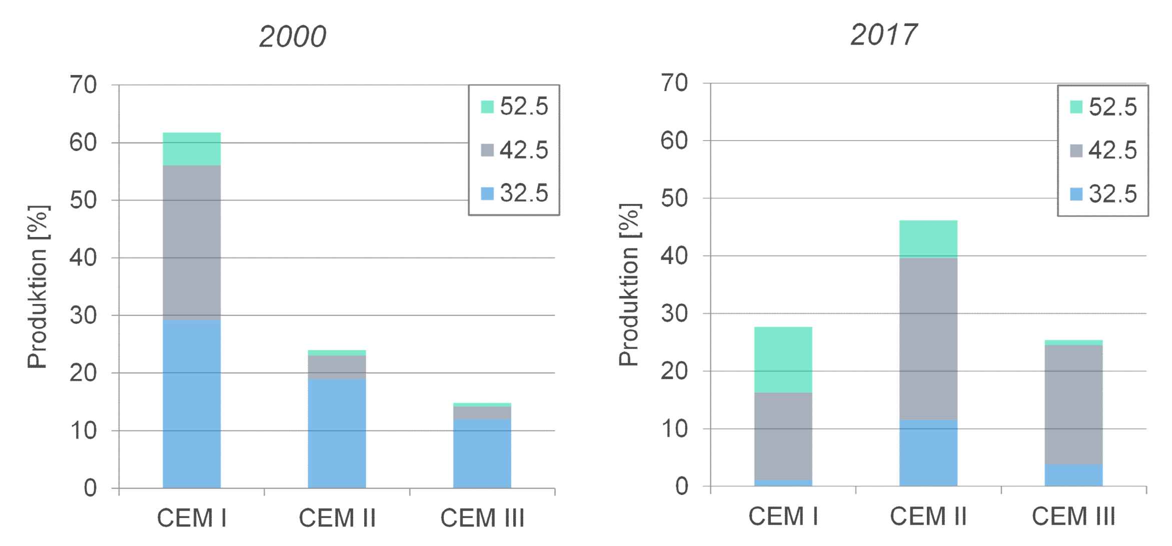

Figure 1 Production of different cement-types and their related strength classes for 2000 and 2017 [VDZ 2019; Pal 2009].

This development shows that the utilisation of various cement components with different grindabilities has increased and that the shift to a higher strength class requires higher product finenesses. However, with increasing cement fineness, the specific electrical energy demand will rise [VDZ 2020a]. At the same time, conventionally used ball mills in closed circuits with classifiers for cement production are reaching their technical limits and are often optimised for only one type of cement. Therefore, the potential for a production of higher product fineness is limited. This means that the development and the utilisation of new process solutions will be very important in the future.

The applicability of separate ultra-fine grinding (SFG) for cement grinding was determined in a previous research project (18853N) with focus on the energy-saving potential for the production of Portland-cements [18853N]. This two-stage grinding process uses energetically highly efficient high-pressure comminution systems for pre-grinding of the main cement components (1st grinding step (GS)). Only a small portion of these pre-ground intermediate products are subsequently ground by means of an ultra-fine grinding aggregate (2nd GS). Ultra-fine grinding means the production of extremely fine products with a percentage passing at 90% (D90) of less than 8 µm [Tre 2020], which cannot be achieved using conventional ball mills. In the first and second grinding step, intermediate products (IPs) of different finenesses are produced, which subsequently are used for mixing Portland cements of various strength classes (Figure 2).

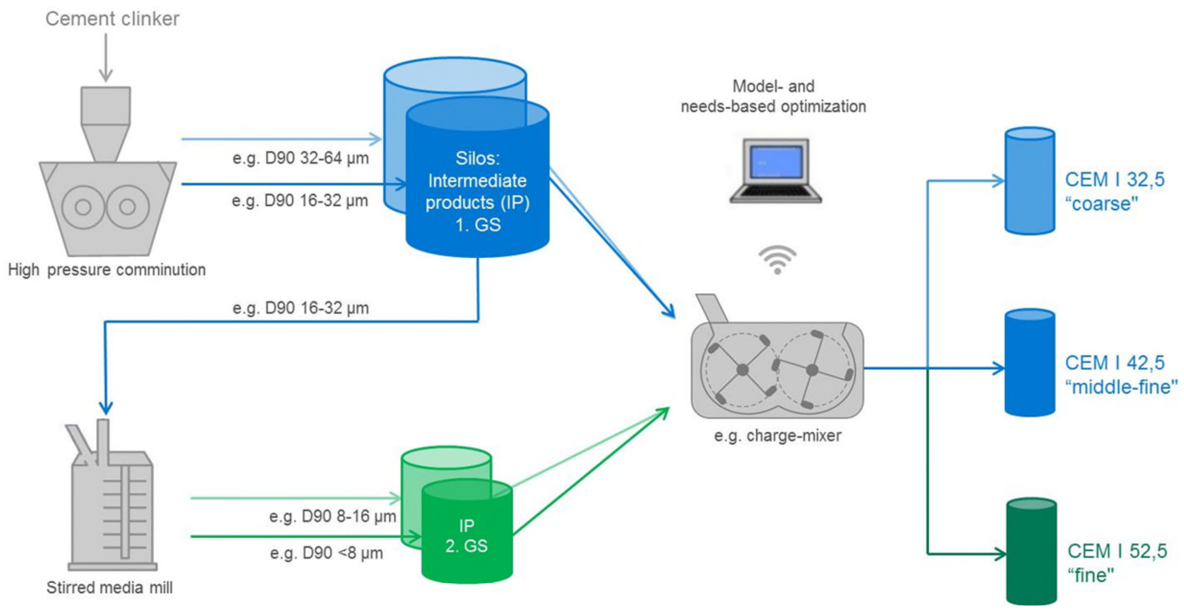

Figure 2 Schematic illustration of separate ultra-fine grinding for the production of Portland-cements [Tre 2021].

A model-based optimisation tool ensures that high mass fractions from high-pressure comminution (1st grinding step) are preferred for an energetically optimal cement mixture. At the same time, the mass fractions from the energy-intensive 2nd grinding step are kept as low as possible. The model calculation also ensures that the resulting particle size distribution (PSD) of the cement blend from SFG is adapted to a typical broad reference-PSD of a ball mill in order to obtain comparable cement properties [18853N].

2 Objectives of the research project

The general principles of separate ultra-fine grinding have already been examined in a previous project (18853N) focussing on Portland cements [Tre 2020]. These principles as well as the scientifically founded rules for the production of cements by means of separate ultra-fine grinding were to be proved and applied in the context of this project using grinding tech-

nologies on a semi-industrial scale. Moreover, the approach of SFG has been focussed on the reproduction of industrial composite cements usually produced via ball mills (BM). In addition to the grinding of the cement clinker, this also included the consideration of other main components such as limestone and granulated blast furnace slag (GBFS).
By using semi-industrial grinding systems such as high-pressure grinding rollers or vertical stirred media mills, the energy-saving potential of SFG can be compared to industrial ball mill production. This energy-saving potential (ESP) is to be demonstrated using a Portland cement and different composite cements.
In addition, the influence of the SFG on the properties of the cement-mixtures produced was to be investigated and evaluated. The final assessment of separate ultra-fine grinding was finally done by the comparison of the results of the cement properties and the derived ESP of the specific electrical energy demand.

3 Scope of the project

The main cement components used in this project include a clinker, a limestone and two granulated blast furnace slags. These main cement components as well as the cement-types obtained as reference-cements were examined chemically and mineralogically. The clinker, limestone and the GBFS A and B were also analysed with regard to their grindability. With the exception of GBFS A, all materials originated from the same cement plant. Clinker, limestone and GBFS A were selected as feed material for the semi-industrial grinding tests. The GBFS B was industrially dried and ground using a vertical roller mill (VRM). Overall, two different fine products were ground with the VRM. Both VRM products were also used in this project, as they are already being produced in an energy-efficient way on an industrial scale. The chemical and mineralogical determinations of both GBFS showed good agreement and the grindability according to Zeisel was well comparable. Cement mixtures containing GBFS B could therefore be used as a comparison with corresponding mixtures derived from SFG and GBFS A. As a result, the energy-saving potential of separate ultra-fine grinding could be compared both with cement production using a ball mill and with energy-efficient production using a VRM.

The reference-cements included a CEM I 42,5R, a CEM I 52,5R and composite cements CEM II / A-LL 42.5N and CEM II / B-S 42.5N. These cements are produced industrially using a ball mill. In addition, a CEM III / B 42.5N was obtained, which was mixed from a fine clinker meal from the ball mill and the GBFS B from the VRM. Table 1 gives an overview of the reference-cements used and their material composition [Kna 2023].

Table 1 Selected cements from the portfolio of the reference-cement plant with the composition of the main components and the grinding technology involved in comminution [Kna 2023].

Grinding strategy	**Cement-type**	**Clinker**	**Limestone**	**GBFS**	**Grinding technology**
Co-grinding	CEM I 42,5R	100 %	-	-	BM
	CEM I 52,5R	100 %	-	-	BM
	CEM II/A-LL 42,5N	~80 %	~18 %	-	BM
	CEM II/B-S 42,5N	~70 %	-	~30 %	BM
Separate grinding	CEM III/B 42,5N	~30 %	-	-	BM
		-	-	~70 %	VRM

The realisation of the semi-industrial separate ultra-fine grinding in the 1st grinding step was done using a high-pressure grinding roller (HPGR) and a vertical stirred media mill (vSMM) in the 2nd grinding step, as shown in Figure 3. In the 1st grinding step, 4 intermediate products of different fineness were ground for each cement component. In the 2nd grinding step, the clinker and the GBFS A were subsequently ground to 3 different ultra-fine products each. Figure 3 shows the grinding systems used in the 1st and 2nd grinding step on a pilot plant scale.

Figure 3 Left: Grinding plant with a high-pressure grinding roller for the production of coarse intermediate products from the 1st grinding step. Right: Vertical stirred media mill, which was used for the subsequent grinding and production of the intermediate ultra-fine products from the 2nd grinding step [Kna 2023].

In order to correctly evaluate the influence of the ultra-fine grinding on the specific energy demand and the cement properties, it was necessary to reproduce the particle size distributions of the reference-cements as precisely as possible. As in the previous project, the reproduction and blending of the reference-PSD were realised using a model-based calculation. The non-linear, iterative calculation approach of the previous project was extended to cements with various main components. The mixture proportions necessary for the "optimal" reproduction of the reference-PSDs were calculated by the model-based tool. The term “optimal blend” should be understood in such a way that there is only little deviation between the cement-PSD originated from the SFG and the reference-PSD. All in all, an optimal mixture of the intermediate products of the separate ultra-fine grinding could be produced for all reference cements and remixed on a laboratory scale.

The laboratory mixes produced by the intermediate products of SFG were subsequently subjected to a determination of the cement properties. The flexural and compressive strengths were tested after 2 and 28 days, and the required water demand and the beginning and ending of solidification were determined. The results of the cement properties were compared with the energy-saving potential of the SFG.

4 Summary of results

The optimal mixture proportions of the individual intermediate products identified by means of the blending calculation were mixed under laboratory conditions and analysed using laser diffraction. The deviation of the laboratory mixture with regard to the respective reference-PSD is very low for all selected cement-types. Figure 4 shows an example of the PSD of the reference-cement CEM I 52,5R and its mixture from the SFG (CEM I_M2.1). The two PSDs are incongruent only in a few measurement points and otherwise show excellent agreement.

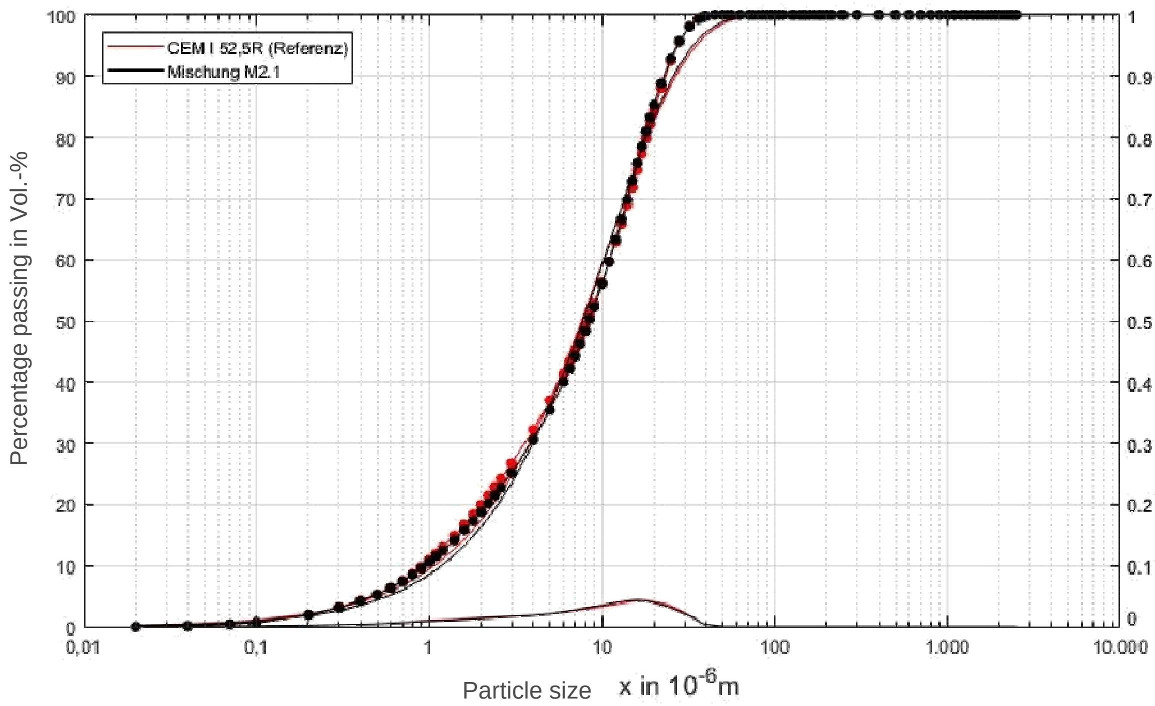

Figure 4 Comparison of the two PSDs of the reference-cement CEM I 52,5R (red) and the mixture made in the laboratory from the SFG (black) [Kna 2023].

The specific energy demand necessary for the production of the SFG mixtures is made up of the respective mixture proportions, the content of sulfate carriers and the specific energy demand required for mixing and homogenization. Figure 5 shows the respective difference between the specific energy demand from the SFG and the industrial production. A negative ΔE indicates that energy can be saved using SFG in direct comparison to industrial production. For the cements CEM II/B-S and CEM III/B containing GBFS, two mixtures were produced from the SFG. The mixtures M4.1 and M5.1 consist of clinker from SFG and GBFS B from the industrial VRM. M4.2 and M5.2 are pure mixtures from SFG, mixed with GBFS A.

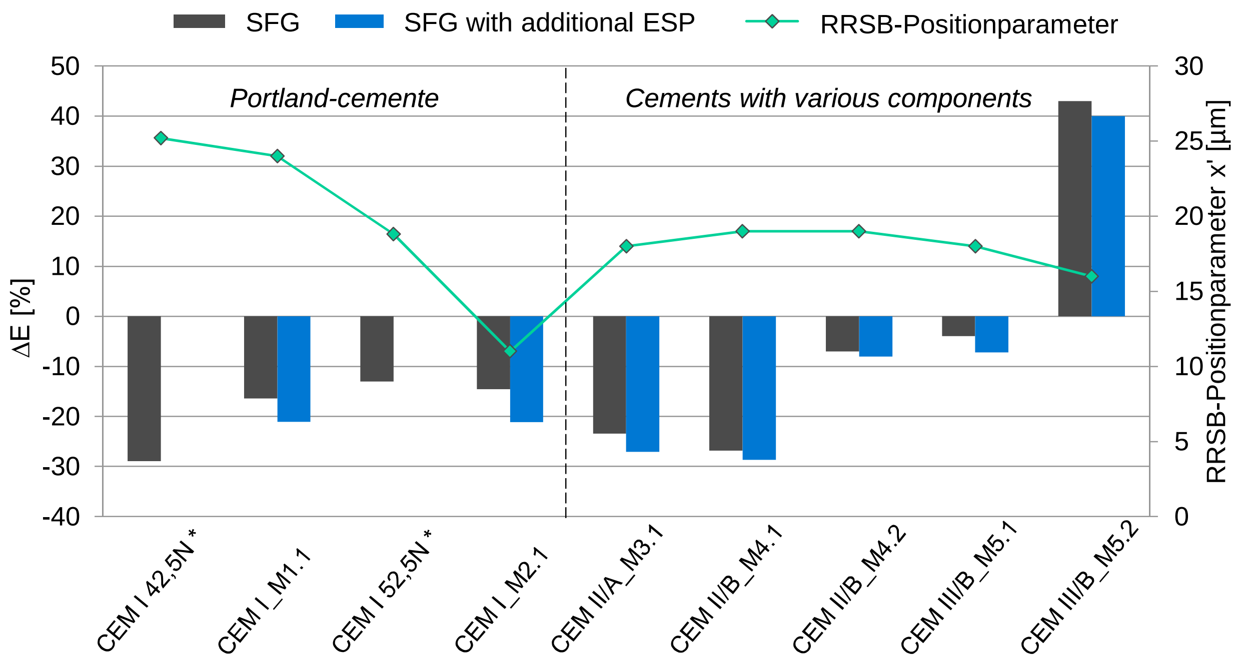

Figure 5 Saving of the specific electrical energy demand for the production of cements by means of separate ultra-fine grinding. The CEM I 42,5N* and CEM I 52,5N* were taken from [Tre 2020]. ESP = Energy-saving potential [Kna 2023].

As shown in Figure 5, it can be seen that both Portland-cements and composite cements can save between 15 and 25 % of electric energy by using SFG, which confirms the results published in [Tre 2020]. An exception is found in the mixture M5.2, which consists largely of GBFS that is difficult to grind and which essentially consists of energy-intensive intermediate products from the 2nd grinding step. Compared to industrial production - mainly using the energy-efficient VRM - the SFG cannot compete if products from a VRM predominate as mixing components. In a direct comparison to BM-cements a very high energy saving potential of up to 30 % can be assumed, taking into account the use of grinding aids in grinding step 1. (SFG with extended ESP in Figure 5, blue bar) [Kna 2023].

The results on the energy-saving potential must consequently be assessed in the context of the related cement properties. For example, the compressive strengths after 2 and 28 days are summarised in Figure 6. With the exception of mixture M4.2, all mixtures from the SFG show lower compressive strengths after 2 and 28 days. The mixtures M4.2 and M5.2 cannot be compared with the cement properties of the respective reference-cements due to the different origins of the GBFS. In spite of the fact that the chemical-mineralogical analysis of the GBFS A and B are in a good agreement, a comparison of the reactivity of both GBFS remains questionable.

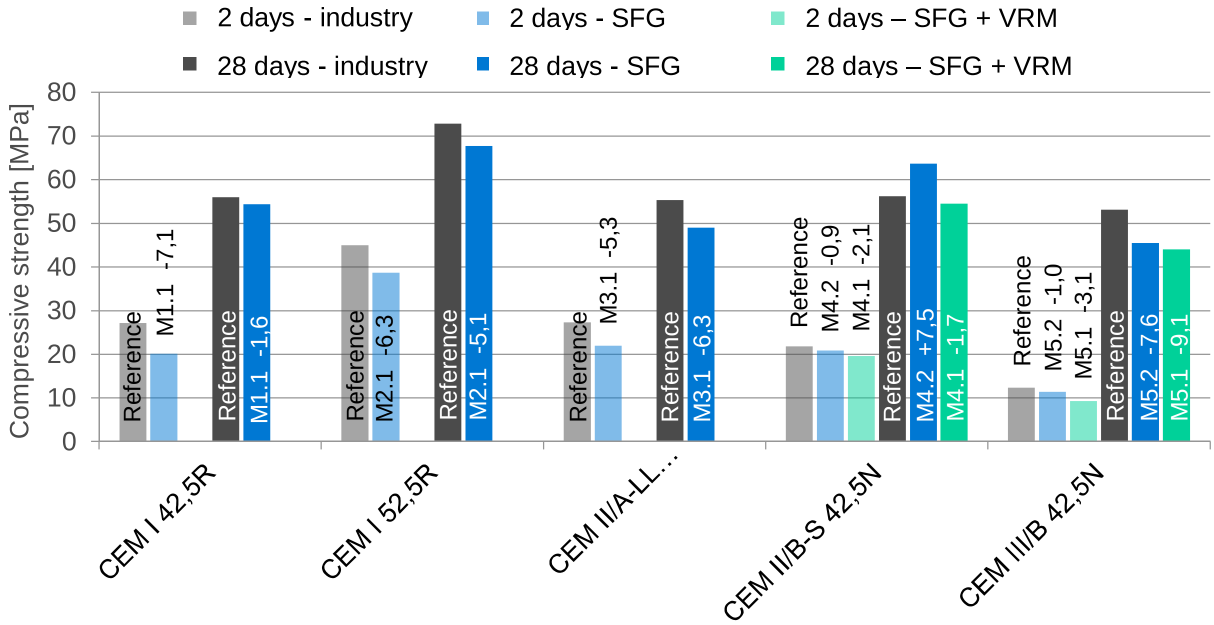

Figure 6 Comparison of the compressive strengths of the reference-cements and the corresponding mixtures which originated from SFG after 2 and 28 days [Kna 2023].

If the different reactivity of the two GBFS used is not taken into account, the increase in compressive strength after 28 days of mixture M4.2 (approx. + 13 %) could also be attributed to an inner gap of the PSD in the slag powder. In this context, this gap is understood to be a gap in the PSD that occurs due to the mixing of intermediate products of very different finenesses. As a result, a certain grain-size is underrepresented within the PSD. Mixture M4.2 shows an indicated gap in the PSD with regard to the GBFS. Ehrenberg in [Ehr 2005] has already demonstrated that the cement properties of slag-containing cements – in particular the compressive strength – can be improved by leaving gaps in the inner PSD of the GBFS. An increase in compressive strength of mixture M4.2 of approx. 13 % could consequently be based on the internal particle size distribution of the GBFS. To prove this statement, however, further systematic investigations are necessary.

As a general result, it can be concluded that the understanding of the influence of the separate ultra-fine grinding on the energy-saving potential and the cement properties could be further expanded. The objective to determine the energy-saving potential of SFG for the production of composite cements was entirely achieved. However, the compressive strengths of the SFG-mixtures are not comparable with those of the industrial reference-cements in all cases. Using the SFG, an optimisation of the cement properties can be expected, if the mixing approach for slag-containing cements described in [Ehr 2005] is followed. For this purpose, a further research project has currently been applied for, in which this potential shall be investigated with regard to clinker-efficient and CO_2-reduced cements such as CEM II/C- and CEM VI-cements.

5 Literature

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Funding notice

The IGF-Project 20656N of VDZ Technology gGmbH, Toulouser Allee 71, 40476 Düsseldorf was funded by the AiF as part of the program to promote the “Industrielle Gemeinschaftsforschung” (IGF) of the Federal Ministry for Economic Affairs and Energy based on a resolution of the German parliament.