Process Technology of Cement Manufacture

Process engineering research aims primarily at optimising the energy consumption and use of manpower in cement manufacture as well as the quality and uniformity of the cement, and at reducing emissions without compromising economic efficiency. The optimisation of secondary fuel utilisation and the exploration of the impact of secondary fuel use on burner operation and environment were two of the major issues on which investigations focused in the past years. The share that secondary fuels account for in the overall energy consumption of the German cement industry has risen to approx. 38% (2003) by now. This means that many kilns are operated at high substitution rates topping 60% in some cases.

Since the BSE crisis in the year 2000, the German cement industry has utilised the thermal content of meat and bone meal on a large scale. The Research Institute has carried out extensive investigations on the effects of meat and bone meal utilisation on product quality as well as kiln operation and emissions. From an operational point of view, especially the effects on chlorine cycles and the behaviour of phosphate in the kiln plant were of tantamount importance. As far as emissions are concerned, the interest chiefly centred on possible effects on NO$_x$ emissions.

The work performed by a VDZ working group which intensively studied the impact of pre-calcining technology and secondary fuel utilisation on the wear and stability of refractory materials also relates to secondary fuel utilisation. This work has been continued and extended to include the entire kiln in the meantime.

The endeavours to simulate the clinker burning process in a computer model and to make use of simulation calculations to optimise kiln systems and investigate scientific questions, respectively, were continued in the period under review. The process model for the entire clinker burning process available at the Research Institute was extended: It now also comprises the elements of the external cycle (conditioning tower, raw mill, dust filter) and the possibility to simulate chlorine and sulphur behaviour as well as alkali cycles. After the corresponding validation by experimental results, the model can now be employed to design or optimise bypass systems, for example.

Investigations in industrial and semi-industrial grinding and classifying plants were used mainly to examine the effects of separate grinding and mixing or intergrinding, respectively, on the particle size distribution of the cements obtained. The comparison of different grinding systems for cement manufacture represents a new subject of main emphasis in the field of mechanical process engineering. Interest focuses on the different product properties obtained in spite of identical particle size distributions, which may ultimately be attributable to different grinding techniques. Corresponding investigations at semi-industrial grinding and classifying plants are being carried out at the Research Institute and at various plant manufacturers.
Energy consumption

Kilns
In the period under review, the licensed kiln capacity of the German cement industry declined from 132 820 t/d (2002) to 130 020 t/d in 2004. The operating permit of one kiln plant expired. As a consequence, the total of kiln plants with operating permits decreased from 70 to 69. The kiln systems operated in Germany today are almost exclusively plants applying the dry or semidry processes, respectively. In addition to that, there are permits for 8 shaft kilns. The average kiln capacity for rotary kilns rose slightly from 2 106 to 2 112 t/d. Tab. I-1 gives an overview on the status of the available kilns. Accordingly, plants with cyclone or grate preheaters, respectively, account for 99.1% of the total capacity. Reaching 88.3% (relative to capacity) in the year 2004, the proportion of cyclone preheater plants grew further. At 11, the number of pre-calcining systems remained unchanged. Of these systems, 8 are equipped with a tertiary air duct. Since their kiln capacity is higher by comparison, pre-calcining systems represent more than one quarter of the installed, licensed clinker capacity of the German cement works.

At 56%, utilisation was significantly lower in the year 2002 than the long-term average. It rose to 61% again in the year 2003, which was primarily attributable to increased clinker exports. Overall, these degrees of utilisation fall considerably short of the long-term average as well. The utilisation figures are based on an assumed availability of the kiln plants of 320 days per year.

Fuel energy consumption
The main use of fuel energy in cement manufacture is for burning the cement clinker. To a lesser extent, thermal energy is also used for drying other major cement constituents, such as blastfurnace slag. To manufacture cement clinker with its characteristic properties, the raw materials, principally limestone marl and clay, are burnt at temperatures of 1 400 to 1 450 °C. Because of the product specifications and the high temperature process which they require, the cement industry is one of Germany’s energy-intensive industries. For this reason the cement industry has always tried to reduce its energy consumption and hence fuel energy costs. Fig. I-1 shows the trend of the specific thermal energy consumption of the cement industry from 1950 to 2003. From 1987 onwards, the new federal states are included in the values. As the diagram illustrates, the burning process in the German cement works is now optimised to such an extent that no noteworthy further reductions can be expected from process engineering measures.

By contrast, the German cement industry succeeded in significantly reducing its specific energy consumption relative to one ton of cement over the last years. It becomes apparent from the cement companies’ data on energy consumption and output, which the Research Institute collects every year, that only a small proportion of this reduction was due to process engineering measures in the years under review. The stepped-up production of cements with several main constituents is of far greater importance. In this way, the German cement industry managed to lower its specific fuel energy consumption relative to the cement quantity produced from 3 510 kJ/kg cement to 2 740 kJ/kg cement over the past 16 years, as can be seen from Tab. I-2. The clinker proportion in the cement dropped from approx. 86% to 76% over the same period.

This development must be seen against the backdrop of the voluntary agreement on climate protection, to which the German cement industry committed itself in 1995 together with other branches of the German industrial community. In fulfilling this voluntary agreement the cement industry contributes to a reduction in climatically relevant CO₂ emissions. It is thus striving to lower its specific fuel energy consumption by 20% from 1987 to 2005.

Tab. I-1: Number and capacity of the kilns with operating permits in Germany in the years from 2002 to 2004

<table>
<thead>
<tr>
<th>Year</th>
<th>Kilns with cyclone preheaters</th>
<th>Kilns with grate preheaters</th>
<th>Shaft kilns</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>Capacity t/d</td>
<td>%</td>
<td>Number</td>
<td>Capacity t/d</td>
</tr>
<tr>
<td>2002</td>
<td>46</td>
<td>116 550</td>
<td>88.4</td>
<td>16</td>
</tr>
<tr>
<td>2003</td>
<td>45</td>
<td>114 750</td>
<td>88.3</td>
<td>16</td>
</tr>
<tr>
<td>2004</td>
<td>45</td>
<td>114 750</td>
<td>88.3</td>
<td>16</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>Clinker production (year) million t/a</th>
<th>Utilisation in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>24.0</td>
<td>56</td>
</tr>
<tr>
<td>2003</td>
<td>25.2</td>
<td>61</td>
</tr>
<tr>
<td>2004</td>
<td>30</td>
<td>61</td>
</tr>
</tbody>
</table>

1) according to CO₂ monitoring 2) assumed availability 320 d/a 3) not available yet
In the past few years there has been a continuous change in the structure of the fuels used in the German cement industry. Since 1987 the total fuel usage has fallen from 119.9 to 91.3 million GJ/a in 2003, which is attributable to the slump in production, among other factors. In absolute terms, this corresponds to a reduction of 23.9%. As can be seen from Fig. I-2, the proportion of secondary fuels continued to rise in the period under review and now totals 38.3% (2003), as against 23.0% in 1999. The increasing use of secondary fuels entailed the substitution of hard coal and, to a smaller extent, petcoke and lignite during the period under review. The consumption of heavy fuel oil decreased from 5.9 million GJ/a in 1999 to 2.7 million GJ/a in 2003.

The breakdown of secondary fuels for the years 2000 and 2003 demonstrates that traditional secondary fuels, i.e. used tires and waste oil, have lost in importance in comparison to other secondary fuels. Tab. I-3 shows that the input of used tires remained nearly constant at just under 250 000 t/a, whereas the quantity of waste oil utilised decreased from 140 000 t/a in 2000 to 116 000 t/a in 2003. The use of fractions from industrial and commercial wastes increased substantially, from 372 000 t/a in 2000 to 626 000 t/a in 2003. Besides, a rise to 155 000 t/a in the utilisation of processed fractions from municipal wastes was recorded. The use of meat and bone meal and animal fat began in 2000 in the wake of the BSE crisis and was increased to 452 000 t/a by the year 2003. It is, however, predictable that these quantities will no longer be available on the same scale in the future.

**Electrical power consumption**

Electrical energy is consumed in cement manufacture primarily for raw material processing (about 35%), for burning and cooling the clinker (approx. 22%) and for cement grinding (approx. 38%). Fig. I-3 shows the trend of electrical power consumption by German cement works in the period from 1950 to 2003. The long-term rise in electrical power consumption could be stopped after the German reunification. This was even followed by a slight reduction in the succeeding years, which reached a new low of 99.5 kWh/t in the year 2003.
Cements with other main constituents in addition to clinker, such as blastfurnace slag or limestone, consume more grinding energy since they need to be ground finer to achieve the same quality. On the other hand, the corresponding electrical power required for the manufacture of substituted clinker (raw material preparation, burning process) will be saved. The use of energy-efficient mill types, such as high-pressure grinding rolls, has gained acceptance in the cement industry. Since the working properties of the cement produced in these mills do not correspond to those of cement ground in customary ball mills, however, subsequent grinding in a ball mill is usually still necessary. Therefore, it is still impossible to realise the full potential of energy saving. Even separating the grinding process of the different main constituents and mixing them subsequently in mixing systems apparently does not allow for significant reductions under regular operating conditions.

### Plant operation

#### Effects of meat and bone meal use on rotary kiln operation

Whenever the fuel type is changed, the effects on kiln operation, emissions and cement properties have to be taken into consideration. The impact of meat and bone meal utilisation on the operation of rotary kilns and cement properties (see Chapter III) was investigated as part of a research project sponsored by the AiF. Besides phosphates, meat and bone meal also have higher chlorine and sulphur contents as well as elevated nitrogen contents, which may influence recirculating material systems in the kiln plant and NO\_x emissions. Furthermore, meat and bone meal particles are markedly coarser than pulverised coal. As a consequence, it may take longer to completely burn up a meat and bone meal particle than a more finely ground coal particle.

Extensive industrial investigations both with and without meat and bone meal use were carried out at three kilns. Furthermore, the feeding point of the meat and bone meal was varied. Two of the kiln plants investigated are classic cyclone preheater kilns, while the third is a pre-calcining system. The kiln trials consisted of investigating the impact of meat and bone meal utilisation on fuel energy consumption, combustion conditions, NO\_x emissions and recirculating chlorine and sulphur systems. The influence of meat and bone meal use on fuel energy requirement was only slight in all three kilns. When meat and bone meal was utilised, the measured raw gas temperatures after heat exchanger were slightly higher at all three kilns than without its use. This resulted in slightly higher exhaust losses, which were, however, eclipsed by other effects in some cases (e.g. lower loss of heat through kiln walls due to coating formation in the kiln, and higher oxygen contents in the raw gas at individual operational settings). Insofar, the utilisation of meat and bone meal does not always lead to higher fuel energy requirements.

Meat and bone meal use in the main firing unit apparently caused a longer flame in the rotary kiln in all three plants. On the one hand, this is indicated by elevated temperatures in the kiln inlet area and in the entire preheater, respectively. On the other hand, a change in temperature distribution on the kiln shell was observed at one kiln system. The average kiln shell temperature of that kiln measured along the entire kiln length at different fuel settings is shown in Fig. I-4. The black curve represents the average kiln shell temperature during the use of pulverised pit coal, shredded light fractions of commercial waste (fluff) and waste oil. The dark blue curve maps the temperature profile obtained when 2.5 t/h meat and bone meal were input in the main firing unit. The quantity of fluff added was kept at the same level as during the first measurement, while the mass flows of pulverised coal and waste oil were reduced. When meat and bone meal was utilised, temperatures in the kiln outlet area tended to be lower, while those in the kiln inlet area tended to be slightly higher. The light blue curve represents the temperature distribution on the kiln shell with 1.8 t/h meat and bone meal being utilised in the main firing system, and 0.7 t/h in the kiln inlet. The other fuels remained unchanged. As a consequence, kiln shell temperatures in the kiln outlet area dropped further, while higher shell temperatures were measured in the kiln inlet area. The microscope pictures of polished clinker sections also corroborate that the meat and bone meal use led to the formation of a longer pre-cooling zone.

The utilisation of meat and bone meal in the main firing unit caused a rise in NO\_x emissions of up to 20% in two of the three rotary kilns. Meat and bone meals have a comparatively high content of fuel-induced nitrogen, which, depending on the oxygen
supply in the sintering zone, can contribute to NO formation during combustion. Experiences gained at other cement works demonstrate that such a rise in NO emissions can, however, be prevented by adapting the settings of the firing unit accordingly. By contrast, the use of meat and bone meal in the kiln inlet or in the calciner led to a reduction in NO emissions in comparison to the use of other fuels. The NO emissions measured were particularly low when blood meal instead of meat and bone meal was input in the kiln inlet or the calciner. Analogous to the experience regarding the utilisation of used tyres in the kiln inlet, the combustion of meat and bone meal in this part of the kiln system generates near-stoichiometric or under-stoichiometric conditions locally, which may result in the suppression of NO formation from the meat and bone meal, or even in a reduction of NO from the main firing unit.

Meat and bone meal input into the calciner was investigated at a precalcining system. Fig. 1-5 illustrates the NO concentrations in the raw gas (relative to 10% O₂) of the plant as a function of the oxygen supply in the kiln inlet. It becomes obvious from the Figure that the fuel type used has decisive influence on the NO formation taking place in the calciner and on NO decomposition, respectively. As far as the fuel type is concerned, the volatile content, the content of fuel-induced nitrogen, the type of bond of the fuel-induced nitrogen, and the fineness of the fuel play a crucial role. When the volatile content is high, fairly large quantities of hydrocarbon radicals and NH₃ compounds are released during fuel pyrolysis, which can contribute to NO decomposition. If the nitrogen content of the fuel is fairly high in addition, significantly larger quantities of NH₃ compounds are released during pyrolysis, which also promote NO decomposition. At approx. 18 wt.%, the nitrogen content of blood meal is markedly higher than that of meat and bone meal (approx. 9 wt.%). With the use of blood meal, the quantity of NH₃ compounds and hydrocarbons formed as intermediate products during pyrolysis, which lead to NO reduction via an SNCR reaction, can therefore be assumed to be significantly higher. The combustion of fuels with a low volatile content (e.g. pulverised coal) takes place much more slowly. Thus, the oxygen available is not consumed as quickly, which results in lower NO decomposition. Furthermore, pulverised coal has a low nitrogen content of merely about 0.6 wt.%. As a consequence, the formation of NH₃ compounds and thus NO decomposition is markedly lower than with meat and bone meal or blood meal being utilised.

In all the cases investigated, the input of chlorine in particular and, to a lesser extent, also the input of sulphur into the kiln system increased due to meat and bone meal utilisation. As the bypass systems were operated at a constant bypass rate during the trials, the higher chlorine input resulted in a rise in the chlorine content of the hot meal. Particularly pronounced intensification in recirculating systems was observed at the kiln at which meat and bone meal use was increased from an original 20% to 40% of the firing heat capacity. As can be seen from Fig. 1-6, the increase from 20% to 40% in meat and bone meal utilisation caused the chlorine content of the hot meal to grow from 1.6 wt.% to 2.5 wt.% within one day. Furthermore, the longer flame accompanying higher meat and bone meal use also resulted in a change in sulphur combination in the clinker. In spite of the increase in the chlorine and sulphur contents of the hot meal, however, coating formation in the preheater was manageable during the trial period. In continuous operation, the rise in the chlorine content of the hot meal would be countered by an adaptation of the bypass rate in order to bring the recirculating chlorine system down to the usual level.

Modelling of the clinker burning process

A process technology simulation model developed at the Research Institute of the Cement Industry can be applied to choose suitable secondary fuels and to evaluate the quantities that can be input into rotary kilns. Furthermore, the programme allows to calculate and optimise the operation of a gas bypass installed at the kiln inlet to limit the chlorine content of the hot meal; coating formation in the preheater was manageable during the trial period. In continuous operation, the rise in the chlorine content of the hot meal would be countered by an adaptation of the bypass rate in order to bring the recirculating chlorine system down to the usual level.
modular structure thus permits the individual and flexible simulation of different plants with regard to the parameters of the individual plant components, the plant arrangement, the modes of operation, and the raw materials and fuels. Application of the model focuses on questions relating to energy and materials, with interactions within the process being of particular interest.

In addition to the above-mentioned studies about the use of secondary fuels and the relieving of chlorine recirculating systems via a gas vent, cost-effective and riskless variations of parameters can be performed with fairly little effort. This allows to make statements on the effects of plant rebuilding measures, such as additional or more effective cyclones in the preheater, and of changes in plant operation, such as a reduction of the sintering zone temperature.

The basis from which all these calculation studies proceed is the reference state of a plant, which is developed in cooperation with plant operators on the basis of measurement results and operating experiences and is to reflect the respective current normal operation of the plant as precisely as possible. The calculations based on parameter variations supply extensive data on the relevant process variables for all plant sections. Evaluation in terms of quality and quantity is effected through a comparison with the reference scenario. The mathematical model is based on generally acknowledged basic principles of process engineering, heat transfer and material science, as well as the process know-how gained from numerous kiln and laboratory trials carried out by Research Institute. The verifiability of the calculated results was repeatedly checked and improved by making calculations for different kiln plants and comparing the results with the measurement values. Limestone calcination, clinker phase formation and the firing of fuels constitute the most important chemical reactions, which are calculated in detail for each section of the kiln plant. Since the fuel ashes are taken into consideration as well, the effects of a change in fuel type can thus be calculated both with regard to the quantity and composition of the exhaust gas (O$_2$, CO$_2$, H$_2$O, N$_2$) and with regard to the clinker phases.

The aspect that is often particularly interesting about a shift in fuel type is the associated change in chlorine input into the plant. Together with sulphur and alkalis, chlorine forms recirculating systems between the rotary kiln and the bottom stages of the preheater or the calciner, respectively. These substances and their compounds evaporate in the kiln and are carried into the preheater together with the gas flow. At low temperatures, they condense there on the meal and the dust as well as on the plant walls, on which coatings are formed. Apart from the higher risk of operational malfunctions due to coating formation, the evaporation and condensation lead to heat being transmitted from the kiln into the preheater. This results in higher energy input via the main firing unit and restricts the quantity of fuel that can be fed to the kiln inlet or calciner firing units.

For that reason, the model was extended to include the elements sulphur (in the form of not easily volatilised sulphate and volatile sulphide), chlorine and alkalis in the form of the chemical compounds K$_2$O, Na$_2$O, KCl, NaCl, K$_2$SO$_4$, Na$_2$SO$_4$, CaSO$_4$ and CaCl$_2$, which generate recirculating systems. These compounds either enter the process in this form via the raw materials and fuel ashes, or they may be generated in the process. Both their input and their formation were incorporated into the model, with the formation processes only being calculated when the boundary conditions, such as suitable temperatures, sufficient availability of reaction partners and a partial pressure in the gas phase below saturation, correspond to those prevailing in practical use. It has been taken into consideration that compounds may both form or be dissociated into their individual constituents, when the temperatures prevailing are high enough. As a consequence, these constituents will again be available for the formation of new alkali chloride or alkali sulphate compounds in the gas phase. Furthermore, the chemical compounds may evaporate and condense. The evaporation process is restricted by the saturated partial pressure in the gas being reached. For that reason, temperature ranges within which these reactions can take place have been defined for all chemical compounds. In this way, the different degrees of volatility of the compounds is taken into account. Depending on whether the reaction is exothermic or endothermic, the calculated reaction conversion will cause the local gas or material temperature to increase or decrease.

Applied under practical conditions, the simulation programme made it possible for the first time to successfully estimate the effects of a change in the input of chlorine, sulphur and alkalis on process temperatures, and on the build-up of Cl, SO$_2$, K$_2$O and Na$_2$O in the hot meal (Fig. I-8). In addition to that, the reduction effect which a bypass gas vent has on recirculating systems was determined in terms of quantity. A maximum chloride content in the kiln inlet meal was defined as criterion for the necessary bypass rate (Fig. I-9), i.e. the quantity of gas relative to the kiln inlet volume flow that is discharged via the bypass. Accordingly, the thermally relevant recirculating chlorine, sulphur and alkali systems can be represented reliably.

The model is currently being extended to include the behaviour of trace elements in order to allow more exact emission forecasts for trace elements to be made in the future, for example as part of environmental
Impact assessments. The behaviour of trace elements in the clinker burning process is determined by the volatility of the compounds they form, and by the degrees of bonding and precipitation in the various plant sections. Besides gas and material temperatures, relevant process parameters are in particular the dust collection efficiency of the cyclone stages, the supply in the meal and dust of high-surface fine fractions conducive to condensation, and the intensity of the recirculating systems of chlorine, sulphur and alkali already calculated by the programme. To gather the data required for setting up the model, plant trials at three kilns were carried out as part of AiF research project No. 13230N, the final report on which is open to inspection at the Research Institute. Methodically, the simulation will follow a description of the behaviour of chlorine, sulphur and alkalis, and will incorporate the trace elements in its first step in their elemental form.

**Recirculating dust systems in the preheater**

Investigations aimed at determining the dust content in the cyclone riser ducts of preheaters form the basis for determining the transfer coefficients of various compounds, such as trace elements, for the cyclones and the cyclone preheater as a whole. If the dust content is known, the dust and meal mass flows passing through the cyclones can be calculated.

First of all, the cyclone preheater of a rotary kiln system is the place where the moist raw meal is dried; on the other hand, already in this area chemical, physical and mineralogical reactions take place, such as the partial calcination of the meal. The fresh kiln meal is metered into the gas riser duct below the top cyclone and carried into the cyclone by the gas flow. The intense mixing of the hot gas and the solid creates very favourable conditions for the heat transfer. As a consequence, a nearly complete temperature equilibrium of gas and meal is obtained. In this process, the gas cools and the material warms up. The thermal energy withdrawn from the gas is thus utilised efficiently for the reactions taking place in the solid material. These are endothermic reactions on the one hand, i.e. reactions that are dependent on energy being supplied, such as the evaporation of the surface water and the expulsion of the CO₂ from the CaCO₃ and the MgCO₃. On the other hand, however, the thermal energy is also required to activate the exothermal reactions, i.e. the reactions which imply a release of energy, such as the conversion of organic carbon to CO and CO₂.

In addition to serving the purpose to mix the gas and the meal to achieve efficient heat transmission, the cyclones have the function to separate these materials again as efficiently as possible. The cooled gas is to leave the cyclone separator with a low dust loading to rise to the cyclone stage arranged above. In the case of the top cyclone stage, it is to be discharged as raw gas. Ideally, all the solid material is to issue from the cyclone in the opposite direction in order to re-enter the gas riser and reach the cyclone arranged below, where it is dispersed in the hotter gas. Collection efficiency of 100%, i.e. the complete separation of gas and solids, is, however, achieved in none of the cyclone stages. For one thing, an increase in cyclone separation efficiency always entails a higher pressure drop and thus an elevated energy requirement for gas transport. In line with a rise in temperature, i.e. from the top to the bottom cyclone stage, moreover, the physical properties of the gas change so profoundly as to render the separation of the materials more difficult. Furthermore, the high temperatures in the bottom cyclone separators require designs that are less efficient in terms of separation, but more resistant to temperature and wear. For example, the dip pipes of the lower stages are of shorter construction, which reduces the separation efficiency of the separator.
The investigations the Research Institute carried out to determine the dust contents were performed immediately above the cyclone covers and below the feeding points for kiln meal or hot meal, respectively, in the cyclone riser ducts. Due to the high dust loading and the coating tendency of the meals at high temperatures, it was not possible to measure the gas velocities and thus the volume flows directly. The volume flows were calculated on the basis of continuous measurements of the gas composition and oxygen balances instead. The suction of the partial gas flows loaded with dust was effected isokinetically using an air-cooled probe and a temperature-resistant filter material made from quartz fibres. As the gas flows in the riser ducts still exhibit a marked swirl generated in the cyclones, the suitable angle for the suction nozzle had to be determined first. The highest dust contents, which can be expected to occur in the main flow direction, were usually obtained at a diversion of about 45° from the vertical. Fig. I-10 depicts the results of dust content measurements conducted in the cyclone riser ducts of three different preheaters. Furthermore, the dust collection efficiency determined for the individual cyclone stages is indicated. The results clearly show that marked recirculating dust systems primarily form in the lower cyclone stages. As a result, the meal mass flow into the bottom cyclone stage may exceed the mass flow of kiln meal fed by a factor of up to three.

In addition to the dust content, the particle size distribution of the meal and dust samples was determined using the Cilas method. The meals turned out to get substantially coarser as they passed the cyclone preheater on their way from kiln meal to hot meal (Fig. I-11). On the one hand, this is attributable to the separation characteristics of the cyclones, which cause the finer grain fractions to be carried upwards with the gas flow in dust form, whereas the fairly coarse solid fractions are moved downwards upon separation. The question whether other effects, such as the formation of durable agglomerates from the hot meal particles which get more sticky as temperatures rise, play a role, too, has not yet been clarified.

**Modelling of combustion in the calciner**

Industrial investigations carried out by the Research Institute of the Cement Industry have revealed that the optimised input of fuel, meal and air in calciners allows to achieve effective NO\(_x\) abatement accompanied by complete burn-out. However, optimising the mode of operation of the calciner frequently implies costly rebuilding measures, e.g. for the rearrangement of fuel or meal ducts. To avoid unnecessary rebuilding costs, the simulation of processes during the burning process and the subsequent implementation of the most promising scheme has proven to be a suitable approach in the field of power plant engineering. VDZ’s working group “Operational performance of precalcining systems” therefore proposed to mathematically represent also the processes in the calciner in order to provide the cement industry with a tool allowing it to weigh up various costly rebuilding measures in advance in the future.

Bearing this in mind, the Research Institute of the Cement Industry (FIZ) is now carrying out a simulation project sponsored by the AiF in cooperation with the chair of energy plant and energy process technology (LEAT) of the Ruhr-university in Bochum and the chair of environmental process engineering and plant technology (LUAT) of the Essen/Duisburg university. The project, which proceeds from the results of a feasibility study, aims to support the operational optimisation of precalciner plants regarding the formation of harmful substances, NO\(_x\) abatement measures and coating formation by means of numerical simulation. The option of a largely secured simulation of processes taking place in the precalciner renders purposeful operational
optimisation easier and can thus reduce the efforts and expenditure for time-consuming and costly trials conducted at kiln plants during operation. Moreover, it gets easier to make sound statements on the technical feasibility of installing precalciners in existing plants to reduce harmful substances by staged combustion. Further areas of application for numerical simulation in this context include the investigation of damage and concept studies on the design, the thermal optimisation, and the versatile utilisation of secondary fuels.

The simulation is meant to mathematically describe processes such as the local interaction between turbulence and chemical reaction, between ignition and extinction influences, between the two phases at high loading, and the turbulent interaction during the particle phase. Approaches to be applied in power station engineering were developed to solve similar questions. Their application under the conditions prevailing in precalciners was examined in a feasibility study sponsored by FIZ. As part of this study, suitable parameters for a modified turbulence model and a radiation diffusion model were determined. With the aid of this simplified model, initial promising results regarding the flow conditions in the calciner were achieved. However, this simplified model allowed to describe the actual conditions in the calciner as an approximation only. Advanced investigations and adjustments are now being carried out as part of the above-mentioned research project to fine-tune the model in terms of flow conditions and the formation of harmful substances. In this process, the model is continually validated by measurement data from the Research Institute of the Cement Industry.

LUAT is pursuing the target to investigate the influence that the high particle loading has on turbulence and radiation characteristics in more detail than before. Initial results show that the radiation processes in a calciner at high solids loading are reflected most precisely by a modified diffusion model. Fig. I-12 represents the temperature distribution in the bottom section of the calciner, where the fuel and meal are fed. The dispersion of radiation on the particles, which is indicated by the dispersion coefficients, has decisive influence on the temperature profile. Accordingly, the best results are achieved, when the dispersion coefficient ranges between 0.2 and 0.5.

The work performed at LEAT focuses on a universally applicable and adequately precise calcination and sulphatisation model as well as the influence of the calcination reaction on the distribution of concentration and temperature and thus on the formation/reduction of pollutants. This work is supplemented by experimental fundamental investigations on pollutant formation in the calciner, and by numerical simulation of the mixing, fuel conversion and heat transmission in the rotary cement kiln and the calciner.

The tremendous influence that the high particle loading has on the formation of pollutants and the calcination reaction with regard to turbulence and radiation became apparent from the work performed previously. As a consequence, the use of special model assumptions was necessary. Many details of the existing model approaches had already been refined and adapted to describe the reaction processes in a calciner more accurately. Further adaptations of the model simulating the pollutant formation mechanism and the model simulating the calcination process turned out to be possible. Fig. I-13 depicts the comparison...
between the calculated and the measured oxygen concentration. Both the results obtained from the calculations of the preliminary study and the current simulation results are listed opposite the measurement results. It becomes obvious from the figures that the model for calculating the gas composition has been improved in comparison to the previous model. The simulation model allows to determine with adequate precision the high-oxygen and low-oxygen zones identified during the measurement. It also becomes apparent, however, that it is not yet possible to simulate the measurement results with the accuracy desired; this applies to the area where the burn-out air is input (metering point 3) in particular.

The partial models of LEAT and LUAT mentioned above are therefore presently being developed further and adapted more precisely to the actual framework conditions. To that purpose, the partial models are continually adjusted and reviewed using measuring and operational data made available by FIZ. The two partial models are to be combined to form one aggregate model subsequently. In addition to the variation of different staging concepts (meal, fuel and air staging), the influence of different coal types used as fuel is to be investigated with the aid of this model. This is to involve simulating the processes in different calciners and comparing them with actual figures. These investigations will continue to be carried out upon consultation of the Research Institute of the Cement Industry.

Refractory materials

During the period under review, the “Environment and process engineering” committee set up a “Refractory materials” working group, which was assigned the task of summarising and describing the current state of knowledge on this subject. The working group originated from the “Operational performance of precalcining systems” working group, which did good spadework. The new working group will be concerned with the following topics:

- Techniques for state diagnosis
- Selection of refractory materials and anchors at different points of use within the kiln plant
- Influence of conditions of use on the consumption of refractory materials and corrosion damage (use of secondary fuels, kiln tyre attachment, improved recuperation in the clinker cooler, hot spot operation in the calciner, etc.)
- Design of the refractory structure in various plant sections
- Modern de-lining techniques
- Repairs in hot state
- Modern installation techniques
- Industrial safety during work on refractory material
- Input control of refractory bricks
- Drying and warm-up procedures
- Parameters of refractory consumption
- Disposal of spent refractory material

Work was started by drawing up forms for the various plant sections and kiln zones, respectively, in order to compile data on the refractory structure, the materials used, the conditions of use and the experiences gained. Moreover, working groups in charge of the various issues were set up.

Both non-destructive methods and drilling are applied to determine the thickness of the residual lining. Preliminary damage (e.g. corrosion symptoms) can usually only be detected by core drilling or breaking out windows. The factors to be taken into account when selecting the quality of refractory materials for the different kiln sections include the conditions of use, the coating behaviour of the kiln feed, the intensity of recirculating material systems, and the planned service life. The kiln inlet area is usually lined with spinel or chamotte bricks having an Al₂O₃ content > 40 %. The other bricks used are made of spinel or magnesite in the transition zone, of hercynite, magnesite, spinel or dolomite in the sintering zone, and of high alumina or spinel in the kiln outlet area. In some cases, the inlet cone and the kiln outlet are also lined with cast compounds. The kiln design has effects on the wear of the refractory material. Two-support rotary kilns usually have a lower refractory consumption than three-support rotary kilns since they are subject to less mechanical stress. Another aspect which is important for the mechanical stress of the refractory material and thus for its wear is the attachment of the kiln tyres. Geared kiln tyres are obviously more advantageous than loose kiln tyres.

The solutions adopted in designing the refractory structure outside the rotary kiln differ depending on the plant section and the plant operator. As a rule, the refractory structure is made up of a working lining and an insulating layer consisting of 1 or 2 layers. Cylindrical sections and arched ceilings are usually bricked up, while plain surfaces are lined both by bricks or prefabricated elements and by spraycast or cast compounds of varying panel dimensions. The provision of expansion joints and their maintenance play an important role for the durability of the refractory material in many plant sections.

The structural elements outside the rotary kiln that are exposed to the most severe stresses include the ceilings of the lower cyclones (Fig. I-14). The anchoring systems in particular are subject to severe corrosion symptoms. For that reason, anchorage frequently consists of a combination of ceramic and steel anchors. Inspection openings should be provided in the cyclone ceilings to allow the state of the cyclone ceilings and the anchoring system to be scrutinised. Prior to installing the refractory lining in the heat exchanger, the condition of the cyclone ceilings must be inspected from outside. When material is removed from cyclone ceilings, it must
always be chiselled off downwards through the control openings. Only upon inspection of the cyclone ceiling through the control openings can the refractory material of the cyclone be scrutinised from inside by means of travelling scaffolds, and the scaffolds and working platforms can be installed when the go-ahead is given. For the sake of hazard prevention in case of simultaneous work at different points, the cyclones should be partitioned by means of needle gates.

Experiences with the gasification of secondary fuels
The selection of a fuel to be used in the clinker burning process depends on its availability, the cost, its fitness for storage, its metering properties, safety requirements, and the interferents it contains. Besides, the physical and chemical parameters of the fuels are relevant, too. Dispersibility, moisture content, particle size, calorific value, homogeneity, the chlorine, sulphur, alkali and phosphate content, the fuel-induced nitrogen content and the content of heavy metals all have an impact on process engineering and on emissions, respectively.

As a rule, secondary fuels are fed directly to the burning process. In principle all the hot spots at which standard fuels are input lend themselves to this process. Depending on the type of fuel to be used, however, fuel metering is costly and time-consuming. It can therefore be reasonable in individual cases to subject secondary fuels to preliminary thermal treatment in a separate plant. As several rotary kiln systems in the cement industry were equipped with such plants over the past years, VDZ’s “Operational performance of precalcining system” working group studied this technology.

Basically, a distinction between two types of plants must be made. With gasifiers, the fuel is pyrolysed in substoichiometric conditions, and the lean gas thus generated is subsequently fed to the calciner as fuel. The energy required is either supplied from outside or released by partial combustion. In precombustion chambers, by contrast, the fuel is converted to a significantly higher extent in over-stoichiometric or slightly substoichiometric conditions, respectively. The energy thus generated is utilised to calcinate the kiln feed. The proportion of fuel not yet incinerated (residual coke) can subsequently be input into the calciner.

Numerous different technologies for the preliminary gasification/precombustion of waste exist at present. The technologies installed at rotary kilns in the cement industry up to now comprise circulating fluidised beds, precombustion chambers and so-called hot discs. To date there is one circulating fluidised bed and one precombustion chamber in operation in Germany. The latter was designed chiefly for the utilisation of entire tyres. Existing operating experience shows that both methods work reliably, but the process engineering efforts implied must not be underestimated. The circulating fluidised bed exclusively lends itself to the utilisation of fairly fine-grained fuels, while the precombustion chamber is designed for rather coarse fuels. Both plants can be disconnected from the kiln system by means of slides, i.e. the kiln can still be run using primary fuels exclusively. The choice of an adequate plant is primarily determined by capital and operating costs, costs accruing for preparatory fuel processing, availability, discharge of interferents and materials forming recirculating systems, safety concepts that may be required, and caps on the possible use of lean gas/residual coke in the calciner and the main firing unit.

The more suited a plant scheme is for a very wide range of secondary fuels, the more flexibility in terms of secondary fuel choice it offers to the operator. The option of shifting fuels frequently is advantageous in this respect as well. The requirements regarding fineness, homogeneity and calorific value of the secondary fuels and their content of substances forming recirculating systems constitute additional criteria in choosing a suitable method.

The plant scheme and the type of waste largely determine the calorific value of the lean gas (3,600 to 36,000 kJ/m³). Gases having a lower calorific value can be utilised in the calciner. Input into the main firing unit currently still causes technical problems and is not applied. The effects of the method on total fuel energy consumption depend on the energy efficiency of the aggregate system on the one hand, and on possible impacts on the raw gas quantity and the recuperation of the clinker cooler on the other hand. Smooth kiln operation presupposes a constant energy supply by the pre-gasification/precombustion system. Moreover, the safety concept of the plant and potential impacts on clinker quality and emissions should be checked diligently.

Tab. 1-4 summarises some selection criteria established by VDZ’s “Operational performance of precalcining systems” working group.

<table>
<thead>
<tr>
<th>Economic criteria</th>
<th>Incorporation into the process</th>
<th>Properties of secondary fuels</th>
<th>Other criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Costs for preparatory processing of secondary fuels</td>
<td>Steadiness of energy input</td>
<td>Fineness of preliminary processing</td>
<td>Thermal degree of efficiency</td>
</tr>
<tr>
<td>Capital costs / operating costs</td>
<td>Utilisation of pre-heated tertiary air</td>
<td>Homogeneity</td>
<td>Safety concept</td>
</tr>
<tr>
<td>Separation of valuable substances</td>
<td>Impact on emissions</td>
<td>Minimum calorific value</td>
<td>Repair during regular operation</td>
</tr>
<tr>
<td>Availability</td>
<td>Removal of substances forming recirculating systems</td>
<td>Flexibility in terms of fuel type shifts</td>
<td></td>
</tr>
<tr>
<td>Possible use of lean gas in the main burner</td>
<td>Separation of undesired fractions</td>
<td>Share suitable for material recovery / correction in case of stoppage</td>
<td></td>
</tr>
<tr>
<td>Use of lean gas at several kiln plants (interconnected solution)</td>
<td>Share suitable for material recovery / correction in case of stoppage</td>
<td>Sensitivity of the plant to substances forming recirculating systems</td>
<td></td>
</tr>
<tr>
<td>Upper limit for the substitution of standard fuels</td>
<td>Effects on plant operation / option to disconnect</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Control of the plant</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Effects on product quality</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Tab. I-4: Selection criteria for pre-gasification / precombustion plants
Dosing of Fe(II)SO₄ to bagged cement

The industry-wide regulation on “Low-chromate cements and products” adopted by the building trade employers’ liability insurance association, industrial health and safety authorities, cement users, the specialist building materials trade and the cement industry in 1999 comprises a bundle of measures aimed at improving industrial safety in the manual handling of cementitious products. The exclusive production of low-chromate bagged cements, which have been on offer throughout Germany since 1997, constitutes one element of this agreement. Under the terms of the industry-wide regulation, the German cement industry undertook to guarantee the limit value of 2 ppm water-soluble chromate content pursuant to the Technical Rules on Hazardous Substances (TRGS 613) in all German bagged cements by adding suitable reducing agents. In the meantime, the German cement industry has come out in favour of manufacturing loose cement in chromate-reduced quality as well.

Reducing agents used are either Fe(II)SO₄ or SnSO₄, which is, however, much more expensive. In comparison to Fe(II)SO₄, SnSO₄ excels by higher storage stability, better solubility and thus higher reduction effectiveness. As a consequence, even significantly smaller quantities (about factor 10 in comparison to Fe(II)SO₄) can guarantee adequate reduction. However, the metering and homogenising technology that needs to be provided must be even more precise than with Fe(II)SO₄.

The precise and reproducible addition of a comparatively small quantity of reducing agent to a large, oscillating mass flow – the cement – involves substantial effort and expenditure regarding plant technology. A plurality of aspects, such as storage, transport, metering, dust removal, pressure relief, interlocking devices etc., including also unforeseen operational states, must be taken into consideration when the individual plants are planned, taken into operation and operationally optimised. The findings derived from this learning process were participant. It turned out that there are different process technology solutions for Fe(II)SO₄ addition which yield satisfactory results. Experiences with SnSO₄ addition had not yet been gained at the time of reporting.

Temperatures exceeding 60 °C should be prevented both during the transport and the fluidising by pulsed air as well as the storage of the Fe(II)SO₄ if possible. In addition to fusing, the gradual separation of hydration water occurs at higher temperatures. This reduces the solubility and thus the effectiveness of the reducing agent. Moreover, the water released can lead to the formation of massive conglomerations that block discharge facilities and conveyance paths. It is therefore important to protect the reducing agent from additional external moisture as well. A measure that has proven its worth in this context is the use of a refrigeration air drier for the compressed air in transport, and shielding the silo from direct sunlight. Moreover, ensuring a high circulation in the storage silo (storage time < 3 weeks if possible) and not exceeding a certain silo filling height (reduction of autogeneous pressure) turned out to be useful in preventing agglomerations as early as in the storage of Fe(II)SO₄.

Since most dosing systems are integrated in existing plants and the concepts pursued thus differ greatly in some cases, individual special features must be taken into account. However, the gravimetric determination of both the cement and the Fe(II)SO₄ and the mixing of the two material flows, for example on a shaking screen above the hopper upstream of the bagging unit, turned out to be convenient in principle. The mix should subsequently be metered into the bagging machine via a cellular wheel sluice with pressure compensation. The design of the plant concept should ensure that no cement bag leaves the bagging unit in case of system malfunctions (e.g. failure of one material flow). Bags already filled must be rejected. To prevent mistakes in the control of the plant, there should further be an operating manual describing not only standard operation, but also the course of action to be adopted in case of malfunctions and during the fill-up and emptying of the bagging unit and the feed bin.

In the actual dosing of Fe(II)SO₄ to the cement (carried out via a cellular wheel sluice in the present example), particular attention must be paid to the following items to avoid metering mistakes:

- Determination of both material flows (cement and Fe(II)SO₄) prior to mixing in order to allow exact dosage
- Advance feeding of the Fe(II)SO₄ to the cellular wheel sluice before adding the cement (better mixing – “coffee-on-milk effect”)
- Pressure compensation in the cellular wheel sluice to prevent uncontrolled mass flows, as well as adjustment of dust removal
- Regular maintenance of metering devices and the cellular wheel sluice
- Suitable safety precautions in case of deviations from standard operation (malfunctions, start-up, shut-down) – studies of hazardous incidents.

With regard to the stability of the Fe(II)SO₄, not only mere handling aspects, but also the temperature of the cement during metering must be paid attention to in order to preserve the effectiveness of the reducing agent. It may therefore be advisable in individual cases to cool the cement.

Apart from the reducing effect of the Fe(II)SO₄, the addition of sulphate agents strongly influences the characteristics of cements from their workability up to their strength development. This is another reason why diligent metering of the reducing agent is indispensable. For example, the dose of chromate-reducing agents added to the fresh concrete as concrete admixtures in the form of heptahydrate is limited to a maximum of 0.5 wt.% pursuant to the approval since cement is already made with optimised sulphate agents in view of its workability. However, a sufficient allowance is inevitable to make sure that the product is safe for users. One value applied for this allowance is the so-called “overdose factor”, which indicates by how much the reducing agent was overdosed beyond the mere stoichiometric requirement as a function of the original chromate content. At an average overdose factor of more than 30, i.e. addition of a quantity 30 times higher than the quantity that would be necessary to reduce the original chromate content to below 2 ppm, the product can be assumed to be safe even after fairly long storage times if storage is appropriate (see Tab. 1-5).
Particle size distribution with intergrinding
The strength of cement made from several main constituents is primarily influenced by the reactivity and the mix proportions of the cement constituents, and to a lesser degree by the particle size distributions of the individual constituents. Intergrinding does not allow to influence the particle size distributions of the constituents separately. They are determined by the grindability of the constituents and the mode of operation of the grinding plant. Constituents that are not easily ground build up in fairly coarse fractions, while those that are easily ground build up in fairly fine fractions correspondingly.

A research project sponsored by the AiF was aimed at investigating whether the mode of operation of the grinding plant influences the fineness and particle size distributions of the individual constituents on top of having an impact on the particle size distribution of the cement as a whole. It has been known from publications that the particle sizes of the components blastfurnace slag and clinker do not differ substantially in cements containing blastfurnace slag which were ground in roller mills. As intensive internal material cycles occur in roller mills, the influence of the circulation factor was of paramount interest.

To investigate the influence of the circulation factor on the particle size distribution of the individual components, the processes taking place in a grinding circuit when several components are interground were first simulated by a computer programme. The simulation calculations confirmed the well-known correlation according to which the slope of the particle size distribution of the classifier fines rises with an increase in the circulation factor. At low circulation factors, also the clinker, which is the more easily ground component, was characterised by higher fineness in the interground product than the blastfurnace slag component (Fig. I-15). However, the discrepancy in fineness decreases with an increase in the circulation factor; thus, the difference between the particle size distributions of the components clinker and blastfurnace slag is only slight when the circulation factor is high (Fig. I-16). The effect observed and described above can thus be attributed to the high circulation factor in these mills.

Tab. I-5: Reduction of Cr(VI) in German bagged cements

<table>
<thead>
<tr>
<th></th>
<th>Value range</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr(VI) content before addition</td>
<td>2 – 18 ppm</td>
<td>9 ppm</td>
</tr>
<tr>
<td>Fe(II)SO₄ input¹</td>
<td>0.1 – 0.6 wt.%</td>
<td>0.32 wt.%</td>
</tr>
<tr>
<td>Overdosage² (stoichiometric)</td>
<td>average overdosing factor &gt; 30</td>
<td></td>
</tr>
<tr>
<td>Average Cr(VI) content in bag</td>
<td>&lt; 0.5 ppm</td>
<td></td>
</tr>
</tbody>
</table>

¹ primarily applied as granular Fe(II)SO₄ · n H₂O, with n = 6-7
² factor = 1 in case of stoichiometric dosage for a reduction of Cr(VI) to < 2 ppm

The results obtained from simulation calculations were verified by grinding tests conducted in the Research Institute’s semi-industrial grinding plant. The mill feed used was a mixture consisting of 50% clinker and 50% blastfurnace slag. The grinding plant was first run in open-circuit mode. Subsequently, grinding was effected in a circuit with the classifier, with both a low circulation factor of about 3 and a high circulation factor of about 10 being set. As expected, the particle size distribution of the mill feed was fairly wide at n = 0.88 in open-circuit grinding. In line with a rise in the circulation factor, the particle size distribution of the mill feed became more narrow, reaching a slope of n = 1.06 at a high circulation factor.
The classifier feed, tailings and fines produced in the grinding tests and the basic materials clinker and blastfurnace slag were chemically analysed, and the clinker and blastfurnace slag contents of the samples were determined by weighted average calculation. The results are shown in Fig. 1-17. It becomes apparent from the figure that the not easily ground component blastfurnace slag mainly builds up in the classifier tailings. The blastfurnace slag content measured there exceeded those in the fresh feed and the finished product by up to 8 wt.%. However, the blastfurnace slag content determined in the classifier feed was higher than those in the fresh feed and the finished product as well. As a result of the increase in the circulation factor from 3 to 10, the blastfurnace slag proportion grew from 57 to 58 wt.% in the classifier tailings, and from 54 to 57 wt.% in the classifier feed.

To determine the particle size distributions of the individual components, the classifier fines were split up into fractions by screening and analysed chemically. The particle size distributions of the individual components were determined by weighted average calculation. The results of the grinding tests corroborated the results of the simulation calculations. In the case of the cement manufactured at a low circulation factor, the particle size distributions differed markedly. By contrast, the differences in the fineness of the individual components observed in the cement manufactured at a high circulation factor were only slight.

Influence of the grinding system on cement properties

The manufacture of cement in different grinding systems usually leads to different particle size distributions. The influence that the fineness and the particle size distribution of the cement have on its properties was investigated extensively in the past decades (see e.g. Activity Report 1996-1999). In a number of more recent investigations conducted by different authors, however, cements manufactured in different grinding systems were found to also possess different properties even though their particle size distribution was nearly identical. The different cement properties observed can be attributed either to different mill atmospheres or to different comminution mechanisms.

The comminution mechanisms used can chiefly be subdivided into pressure, beater and impact comminution as well as abrasion. While high-pressure grinding rolls primarily crush by pressure, a combination of comminution mechanisms is applied in vertical roller mills and ball mills. The Research Institute is currently investigating the influence of grinding systems on cement properties, when the particle size distribution is identical. These investigations, which are conducted as part of a research project sponsored by the AiF, consist of grinding different clinkers and blastfurnace slags to identical particle size distributions in different semi-industrial grinding plants. Two fineness levels, about 3 000 and about 4 000 cm²/g, respectively, are being set. Grinding is performed in a semi-industrial vertical roller mill at the physical laboratory of Gebr. Pfeiffer AG in Kaiserslautern, in semi-industrial high-pressure grinding rolls at KHD Humboldt-Weidag AG in Cologne, and in a semi-industrial closed-circuit grinding plant comprising a ball mill and a classifier at the Research Institute of the Cement Industry.

Up to now, the results of corresponding grinding processes with 2 clinkers have been available. It turned out to be possible to produce clinker meals with nearly identical particle size distributions in the different grinding systems by choosing appropriate settings of the operating parameters. Fig. 1-18 exemplifies the particle size distributions generated for a clinker which had been ground in the grinding systems mentioned above. The fineness of the clinker meals totalled 4 130 cm²/g in the vertical roller mill, 4 160 cm²/g in the high-pressure grinding rolls, and 4 150 cm²/g in the ball mill. The clinker meals were subsequently mixed with anhydrite and hemihydrate meal, and the cement properties were determined.

The water demand and setting behaviour of the cements manufactured in this way hardly differed at all. The standard compressive strengths are shown in Fig. 1-19. The cement made in the high-pressure grinding rolls possessed higher strength after 2 days, and the cement ground in the ball mill lower strength after 28 days, than the respective cements manufactured using the other grinding methods. The standard compressive strengths of the corresponding clinker meals with a fineness level of approx. 3 000 cm²/g did not confirm these differences. Although the cement made...
in the high-pressure grinding rolls again possessed a slightly higher 2-day strength than the cements manufactured using other grinding methods, its 28-day strength lagged behind that of the cements ground in the ball mill and the vertical roller mill. As the number of samples is currently still too low, these results cannot be generalised yet.

Moreover, the question of whether the clinker meals manufactured in various grinding systems differ in terms of their grain shape is being looked into as part of the research project. To that purpose, an analysis instrument is used in which the clinker meal is dispersed by means of compressed air and is precipitated on a specimen slide. The individual particles are recorded optically by means of a high-resolution camera and measured by image evaluation software. In each measurement, a total of 10 grain shape parameters (e.g. average diameter, circumference, roundness, ratio of maximum length and width) is determined for 25,000 individual particles. By way of example, the roundness of the particles of a clinker meal is plotted against their average diameter in Fig. I-20. The value 1 on the ordinate stands for the ideal roundness of a particle. Needle-shaped particles have a value near 0. As only few measurements had been completed by the time the present report went to press, a comparative statement on the differences in grain shape as a function of the grinding system cannot yet be made presently. Additional chemico-mineralogical examinations on the clinker meals obtained by different grinding methods are planned. The main focus will be placed on the question of whether the individual clinker phases build up in different particle size ranges when different comminution mechanisms are applied.

Further grinding processes with blastfurnace slag, which are to be carried out on the 3 different semi-industrial plants, are presently being prepared. The blastfurnace slag meals produced are to be investigated with regard to the vitreous structure of the blastfurnace slag first; in this process, different methods are to be applied. Moreover, the properties of blended cements made from these blastfurnace slag meals will be examined.