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SUMMARY

Fibre cement products are used as construction materials, for example as façade boards and as flat and corrugated sheets. Long-lasting building materials made from fibre cement are composite materials based mainly on Portland cement, cementitious materials, mineral fillers and several types of fibres. The fibres typically consist of synthetic organic materials or of cellulose, and reinforce the tensile strength of the products. The products have a service life of several decades, and already during the manufacturing process the question of sustainability is becoming more and more important. As the bulk chemical composition is similar to Portland cement clinker, the end-of-life material can be used as an alternative raw material for the production of clinker. The present study was performed by using samples of recently produced and of naturally and artificially aged fibre cement products in order to evaluate potentials and limitations of the use of fibre cement material as an alternative raw material. With respect to the chemical main constituents, there is hardly any limitation of the fibre cement material proportion when blending the conventional resource with pure corrective materials. Process conditions and clinker quality enable substitution ratios of 15 to 20 % if the materials are fed to the kiln inlet. At this replacement level, a carbon dioxide saving of around 10 % is achieved, and the thermal energy consumption for the clinker burning is lowered by around 300 kJ/kg clinker due to the use of carbonate-poor material. Changes in pollutant formation limit the substitution of conventional raw material fed to the preheater to less than 1 %. Small quantities of fibre cement products are today used in a few cement plants in Europe as a component of the raw material. Due to the low substitution ratio of less than 0.4 %, the mill and kiln operation, the process and the clinker quality are not affected.

(English text supplied by the authors)

ZUSAMMENFASSUNG

Faserzementprodukte werden in Fassadenverkleidungen sowie in flachen und gewellten Platten verwendet. Langlebige Baumaterialien aus Faserzement sind Kompositmaterialien, die im Wesentlichen aus Portlandzement, mineralischen Zusatzstoffen und Füllern sowie aus verschiedenen Fasern zusammengesetzt sind. Die Fasern bestehen typischerweise aus synthetisch hergestellten organischen Materialien oder Zellulose und verstärken die Zugfestigkeit der Produkte. Die Produkte besitzen eine Gebrauchsdauer von einigen Jahrzehnten, jedoch wird die Frage nach der Nachhaltigkeit ihrer Nutzung bereits während der Herstellung immer wichtiger. Da die chemische Zusammensetzung ähnlich derjenigen von Portlandzementklinker ist, kann das rückläufige Material nach der Nutzungsphase als Substitutionsmaterial für die Klinkerherstellung verwendet werden. Die vorliegende Studie wurde mit Proben von kürzlich hergestellten Faserzementprodukten sowie von natürlich und künstlich gealterten Produkten mit dem Ziel durchgeführt, die Möglichkeiten und Grenzen von Faserzementmaterialien als alternatives Rohmaterial zu bewerten. In Bezug auf die chemischen Hauptkomponenten gibt es praktisch keine Begrenzung des Anteils der Faserzementmaterialien in der Rohmaterialmischung, wenn reine Korrekturstoffe verwendet werden. Ofenbetrieb und Klinkerqualität ermöglichen Substitutionsraten von 15 bis 20 % bei der Zugabe in den Ofeneinlauf. Auf diesem Substitutionsniveau wird eine Kohlendioxideinsparung von etwa 10 % erzielt, wobei der thermische Energiebedarf für das Klinkerbrennen aufgrund der carbonatarmen Bestandteile um etwa 300 kJ/kg Klinker gemindert wird. Veränderungen in der Schadstoffbildung begrenzen die Substitution des konventionellen Rohmaterials bei Zugabe in den Vorwärmer auf weniger als 1 %. Heute werden in Europa geringe Mengen an Faserzementprodukten als eine Komponente des Rohmaterials in einigen Zementwerken genutzt. Aufgrund der geringen Einsatzmengen des Rohmaterials von weniger als 0,4 % sind der Mühlen- und Ofenbetrieb, der Prozess und die Klinkerqualität nicht beeinträchtigt.

The use of fibre cement refuse as a raw material substitute for cement clinker production

Die Nutzung von Faserzementabfällen als alternatives Rohmaterial für die Herstellung von Zementklinker

1 The use of fibre cement production residues as an alternative raw material for cement clinker manufacturing

Fibre cement products are long-lasting building materials. Typical applications of these materials are fire protection and partition walls, ceilings and floors, and external cladding and roofing such as corrugated sheets and flat slates for base and architectural facing. ❱ Fig. 1 shows some typical products made from fibre cement.

Air-cured fibre cement products are composite materials based mainly on Portland cement, a variety of supplementary cementitious materials (SCMs) and mineral fillers, and different types of fibres. The fibres give tensile and flexural strength to the products. The reinforcement fibres typically consist of synthetic materials, while cellulose fibres are used for a bond between the synthetic fibres and the mineral compounds. These products have a typical service life of 60 years, and already during the manufacturing process the question of their further use or disposal after their service life is becoming more and more important.

Today, retrieved fibre cement materials originate from production residues of the manufacturing process. In spite of the long service life of the building materials, the fibre cement industry is preparing itself to establish recovery and recycling systems for fibre cement product refuse from demolition waste. In the coming decades the fibre cement industry expects an increasing demand for an appropriate treatment of returned fibre cement materials to arise. Besides the recovery of the building products, the recycling of these materials after their service life is also an option. As many fibre cement products contain a high amount of Portland cement, SCMs and calcitic fillers, the bulk chemical composition of their inorganic components is similar to Portland cement clinker. The refuse material from refurbishment and demolition can therefore be used as a substitute material for the production of Portland cement clinker. ❱ Fig. 2 illustrates the loop of using fibre cement refuse as a raw material for clinker, which in return, via the cement made with it, can be used for fibre cement products.

Already today, low quantities of production residues are being used in clinker manufacturing as an alternative raw material. As by now fibre cement-based construction material has been used for more than several decades, refuse from the refurbishment and demolition of buildings is expected in the near future. Therefore, the Research Institute of the Cement Industry, Duesseldorf, Germany, and Redco NV, Kapelle-op-den-Bos, Belgium, conducted a study on the potentials and limitations of the use of fibre cement materials as a raw material substitute in cement clinker manufacturing. As nowadays fibre cement refuse is still unavailable and demolition waste is not yet readily available, the present study was performed by using fibre cement product samples of recent production, as well as samples taken from naturally and artificially aged fibre cement products. Four groups of air-cured fibre cement production residues were characterised chemically and the results were assessed with respect to the substitution of raw materials within the production of cement clinker.

Based on the analyses results, the release of organic compounds was estimated. Model calculations were used to evaluate technological aspects such as impacts on energy consumption, carbon dioxide emissions, kiln operation, clinker quality and maximum quantities and limitations in the use of fibre cement materials. The study also summarises some operational experience of cement plant operators using air-cured fibre cement production residues as an alternative raw material. At the time of publication, the Research Institute is conducting a similar study for autoclaved fibre cements. In autoclaved fibre cement products the strength is based on hydrothermally formed calcium silicate hydrates.

2 Chemical characterisation and usability evaluation of typical air-cured fibre cement products

2.1 Materials and methods

The potentials and limitations of the use of fibre cement products as a raw material substitute were evaluated by a chemical characterisation of 20 air-cured fibre cement product samples. The samples originated from production residues and test

Figure 1: Compilation of roofing products made from fibre cement (Photos: Redco NV)

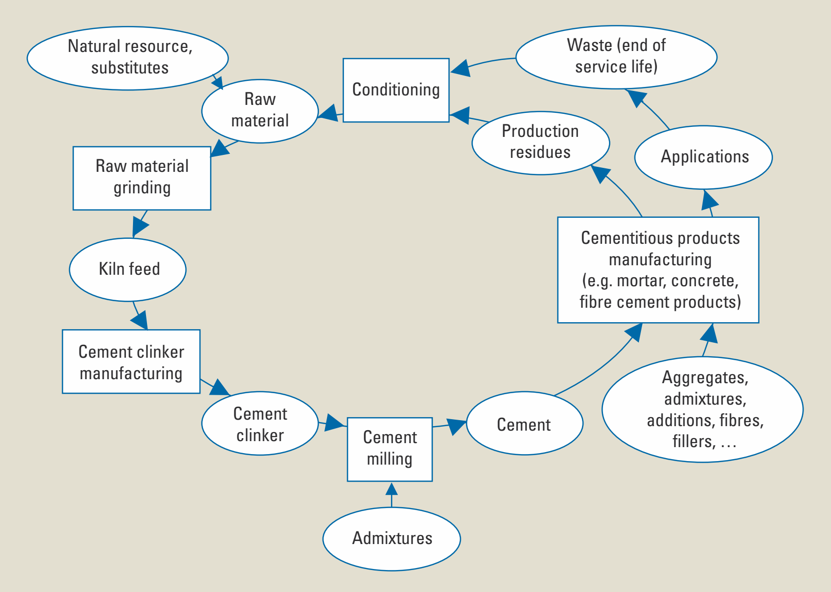


Figure 2: Recycling of fibre cement products as raw material for cement clinker production

facilities. Six flat boards and 14 corrugated sheets represented the variety of formulations of these products as well as different production sites in France, Great Britain, Spain and Germany. The samples were categorised into four groups: flat façade boards (group I), corrugated sheets with standard formulation (group II), corrugated sheets with formulation containing ground granulated blastfurnace slag (group III) and naturally or artificially exposed and carbonated samples (group IV).

All samples were ground to analytical fineness in a cryogenically cooled mill. The main element composition of the samples was analysed with X-ray fluorescence (XRF) performed on fused beads. The content of carbon dioxide (CO_2) bound in inorganic compounds was analysed according to EN 196-2. The content of organically bound carbon (total organic carbon, TOC) was measured according to EN 13639. The loss on ignition (LOI) was determined by heating the samples to 950 °C. The presence of hydrocarbon molecules from the fibres led to artefacts in the analysis of the water content in the samples. Therefore, the water content was calculated as the difference between the LOI and the sum of carbon dioxide and TOC and is marked as H_2O_c. The chloride content was analysed both according to EN 196-2 (Cl^- in inorganic materials) and according to EN 14582 (Cl^- in organic materials).

Table 1: Minimum and maximum contents of chemical compounds in the fibre cement product samples (20 samples covering different formulations)

Compound	**Minimum content** [mass %]	**Maximum content** [mass %]
TOC	1.75	3.78
CO_2	0.74	15.88
H_2O_c	15.03	25.24
CaO	36.92	49.35
MgO	0.58	3.04
SiO_2	16.15	21.48
Al_2O_3	2.86	5.69
Fe_2O_3	1.40	3.30
K_2O	0.10	0.76
Na_2O	0.05	0.26
SO_3	0.98	2.27
TiO_2	0.17	0.71 (7.02)3)
Mn_2O_3	0.02	0.09
P_2O_5	0.03	0.39
Cl^- 1)	0.02	0.04
Cl^- 2)	< 0.010	< 0.010

1) Acc. EN 14582
2) Acc. EN 196-2
3) High TiO_2 content due to special formulation for white façade boards

2.2 Analytical results

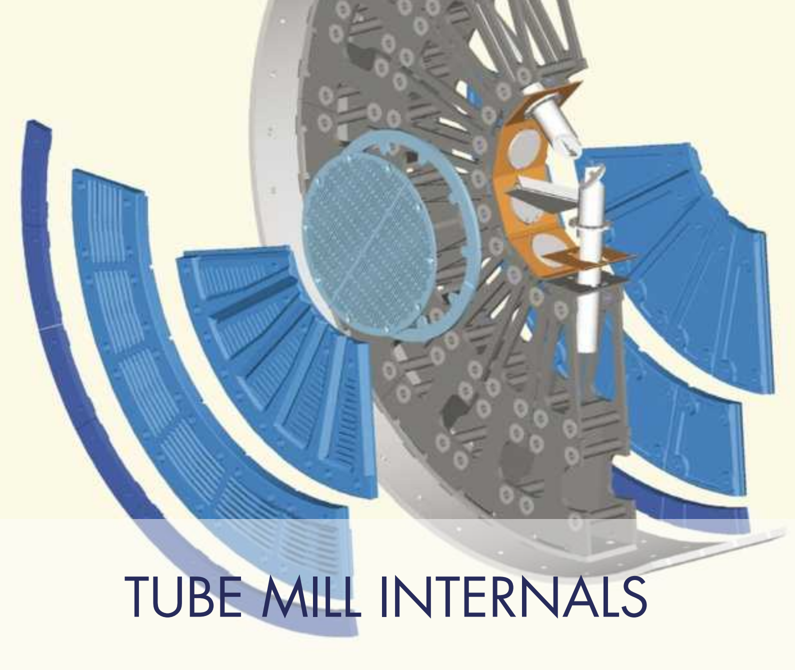
The results of the chemical analyses are summarised in ❱ Table 1 in the form of the minimum and maximum contents of each compound. The chemical compositions of one representative sample per group are illustrated in ❱ Fig. 3.

The highest CO_2 contents occurred in group IV with naturally and artificially carbonated samples. One sample in group I contained a relatively high amount of TiO_2 (7 mass % on a LOI-containing base), in all other samples the TiO_2 content was below 1 mass %.

2.3 Result assessment

The usability of the fibre cement product samples as alternative raw materials for the production of Portland cement clinker was chemically evaluated on the LOI-free proportions of the analysed samples. Only this proportion contributes material to the clinker formation. The LOI leaves the process with the flue gas mainly as water or carbon dioxide.

The LOI-free portions of nearly all samples contained between 94.7 and 99.0 mass % of the main constituents of Portland cement clinker (CaO, MgO, SiO_2, Al_2O_3 and Fe_2O_3). Considering only these oxides, the samples are chemically very similar to Portland cement clinker (❱ Fig. 4). This can be ascribed to the high cement contents in the fibre cement products. Deviations from usual clinker compositions as shown in Fig. 4 mostly result from an undersaturation of CaO, generally due to SiO_2-rich materials used as an aggregate or addition in the initial fibre cement formulation. Additionally, some samples contained relatively high amounts of MgO or Al_2O_3 in their LOI-free proportions compared to the usual clinker compositions. These differences should be balanced by the use of corrective materials in the raw meal. Calculated on a LOI-free basis, a clinker with typical contents of CaO, MgO, SiO_2, Al_2O_3 and Fe_2O_3 could theoretically be achieved with a raw material mixture consisting only of about 75 up to 100 mass % of the sample materials and of chemically pure corrective materials. However, if a specific clinker composition needs to be achieved, the chemistry-based potential substitution ratio of the analysed sample materials in the raw meal might be significantly lower.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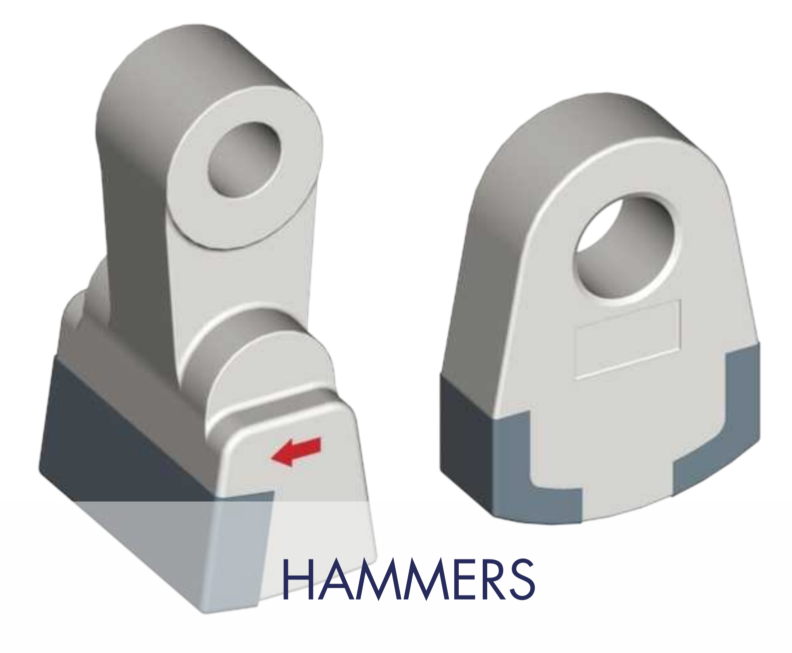
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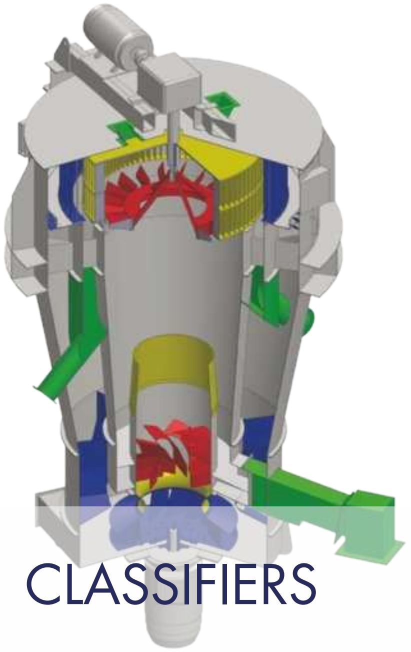
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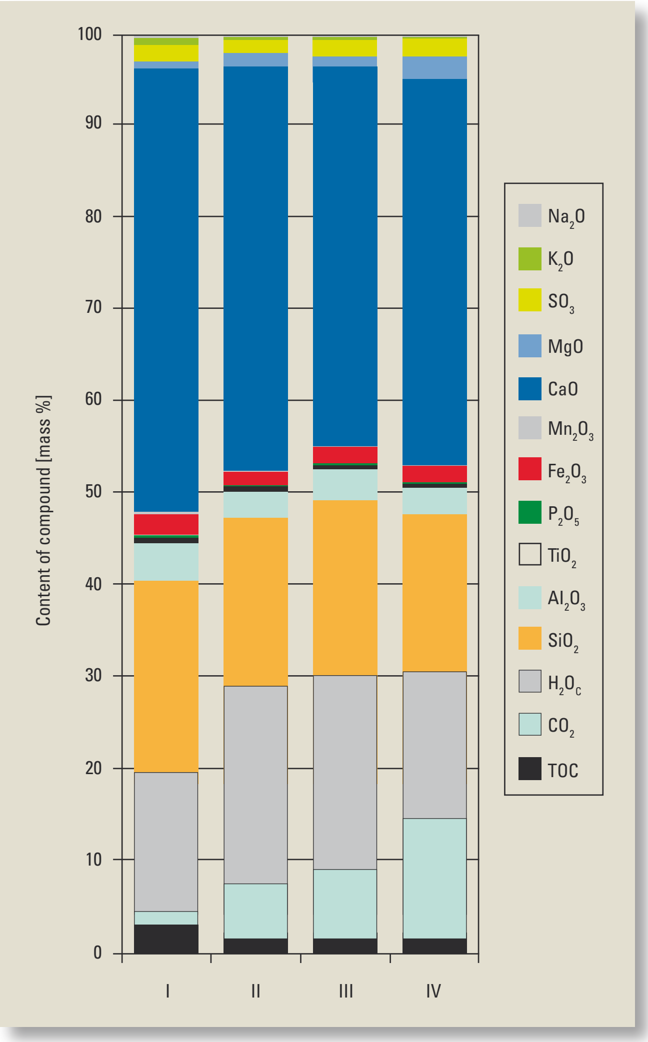


Figure 3: Chemical composition of one representative sample from each sample group. Group I: flat façade boards, group II: corrugated sheets with standard formulation, group III: corrugated sheets with formulation containing ground granulated blastfurnace slag, group IV: naturally exposed and artificially carbonated samples

Besides the main constituents of Portland cement clinker, other main element oxides also have to be considered in the evaluation. The Na_2O-equivalent in the LOI-free proportions of the fibre cement product samples did not exceed 0.94 mass %, which is in the usual range of Portland cement clinker. One sample contained a high amount of TiO_2 (8.8 mass % in the LOI-free portion). Since Portland cement clinker usually contains less than 0.5 mass % of TiO_2 [1], higher amounts of TiO_2 might affect the clinker properties [2]. The usability of this type of material in the clinker burning process would probably be limited to less than 10 mass % in the raw material mixture. However, high TiO_2 contents in fibre cement products are limited to special formulations for products with white colouration to the core. Therefore these materials can easily be traced based on their colour. Additionally, the relevance of this case for the overall evaluation of the usability of fibre cement products for Portland cement clinker production is limited due to the limited market share of products with this specific formulation.

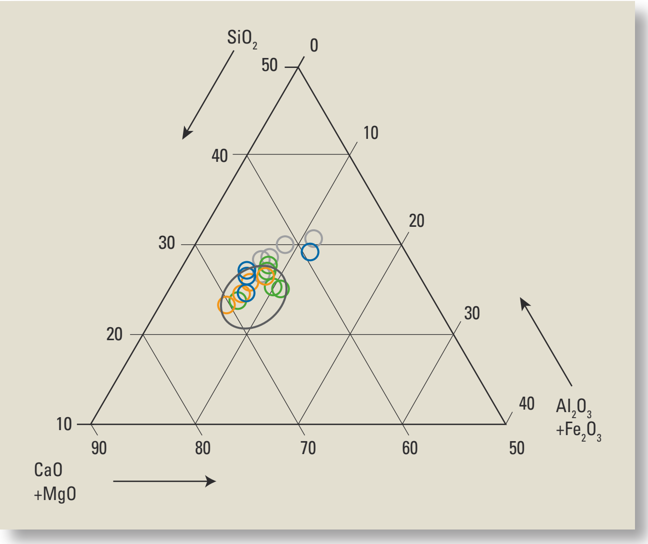


Figure 4: Ternary plot of the analysed samples in the system (CaO+MgO), (Al_2O_3+Fe_2O_3), SiO_2, based on composition in mass %. Green: group I, blue: group II, grey: group III, orange: group IV. The area typical for Portland cement clinker is plotted for comparison (black circle).

The contents of SO_3 in the LOI-free sample proportions were relatively high compared to Portland cement clinker and ranged between 1.4 and 3.1 mass %. This can be ascribed to the sulphate bearing agent in the cements used for the manufacturing of the fibre cement products. The high sulphate contribution of the materials to a raw material mixture would lead to a very high degree of sulphatisation of the clinker and affect the clinker and cement properties (phase composition, crystal sizes, setting behaviour) as well as the clinker burning process (formation of coating, build-up of cycles) significantly [3]. Therefore, this factor would probably limit the quantity of fibre cement products usable in the clinker burning process.

3 Use of fibre cement materials in clinker manufacturing

3.1 Conditioning of fibre cement materials

Today, fibre cement material is retrieved as residues from the production process, and, in the future, product refuse from demolition waste is expected. As the material consists of different shapes and sizes, the fibre cement materials have to be pretreated before they can be used as a raw material substitute in the clinker manufacturing process. An appropriate treatment is a comminution by shredding or crushing. The downsized fibre cement production residues can be blended with the conventional raw materials, ground and fed as mixed kiln feed to the top cyclone stage of the preheater. Coarse particles can be fed to the kiln inlet. ❱ Fig. 5 displays the diagram of the material and gas flows in a calciner plant for cement clinker manufacturing. From an operational point

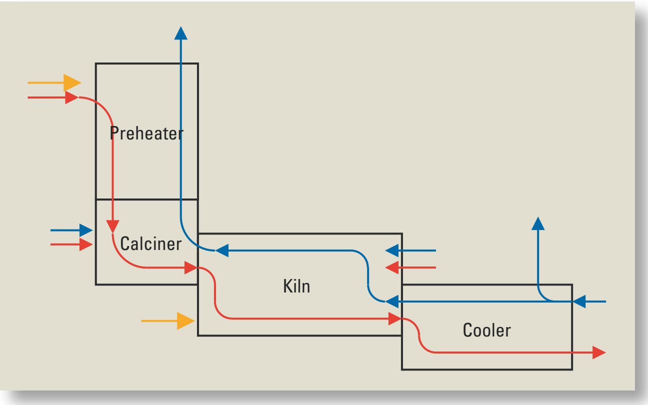


Figure 5: Flow sheet of air and gas streams (blue), kiln charge and fuel flows (red) and the possible feeding locations (orange) of the fibre cement materials

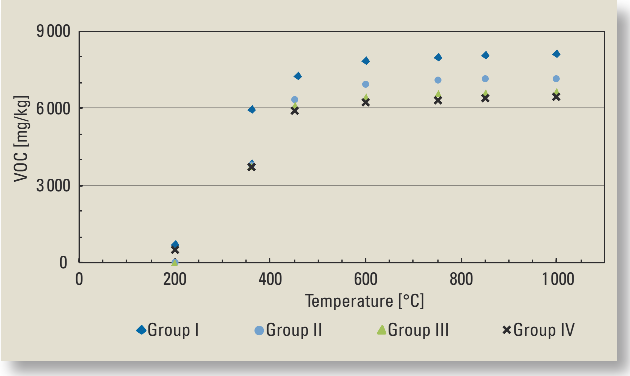


Figure 6: Release of volatile organic compounds (VOC) expressed as carbon of one representative sample from each sample group (cumulative curve)

of view the feeding of the residues into the pyroprocess can occur at two locations:

- feeding of ground fibre cement production residues blended with the conventional kiln feed to the preheater
- feeding of crushed residues to the kiln inlet

3.2 Emissions caused by the use of fibre cement materials

The reinforcement fibres consist of synthetic fibres based on polyvinyl alcohol, polypropylene and in some products also polyethylene pulp is used as stabilising additive. All these synthetic fibrous products are made from polymerised hydrocarbons. Fibres retrieved from cellulose pulp are also used. During the heating of the fibre cement products and residues, organic compounds are released from the fibre cement materials. In order to evaluate the organic emissions caused by the fibre cement materials the production residue samples were uniformly heated to 1 000 °C and the evaporated volatile organic compounds (VOC) were analysed and related to the temperature. The chart in ❱ Fig. 6 illustrates the cumulative release of organic compounds per unit mass as function of the temperature. Due to a mixture of fibres of various sources the major part of the organic release evaporated in a temperature range between 200 and 450 °C, but a release of organics up to 1 000 °C was also observed. Based on a specific preheater exit gas volume of 1.8 m^3/kg clinker and 1.1 m^3/kg kiln feed (the sum of conventional and fibre cement products' feed) respectively, the VOC concentrations expressed as carbon were estimated. This specific preheater exit gas volume reflects the usual figures of a mainly alternative fuel-fired calciner plant described in the Reference Document of Best Available Techniques in the Cement, Lime and Magnesium Oxide Manufacturing Industries [4].

The volatilised VOC in the preheater exit gas are expressed as volatilised carbon per 1 percentage point (%-pt.) substitution of conventional kiln feed by fibre cement production residues. The substitution of conventional raw meal by non-exposed façade boards (group I) raises VOC concentration expressed as carbon by 79 mg/m^3 per %-pt. on average. Corrugated sheets of group II raise the VOC concentrations by 63 and those of group III by 62 mg/m^3 per %-pt. In group IV the results show a wide-range spread of figures due to the different history of the samples. Group I samples show significantly higher concentrations of organic compounds in their initial formulation than the other samples, so VOC emissions arising from façade boards are the highest. No significant differences in VOC formation between the standard formulation (group II) and the formulation with ground granulated blastfurnace slag (group III) were found.

According to the different stages in the service life, fibre cement products refuse can be contaminated by deposition of suspended substances and biomaterial (moss, fungi and microbes). Therefore, the release of volatile organic compounds from the use of material retrieved from refurbishment and demolition waste might even be higher than the estimated figures mentioned above.

Usually in conventional kiln feeds VOC concentrations expressed as carbon do not exceed 100 mg/kg [5]. Fibre cement production residues contain volatile organic compounds in a range of 5 500 to 9 200 mg/kg carbon in the residue samples. Depending on the VOC composition and used technology this may lead to additional VOC emissions. Therefore, in daily operation a substitution of conventional kiln feed up to approx 1 % can be achieved if the fibre cement material is blended to the kiln feed and fed to the preheater. In order to avoid an increase of organic emissions, larger quantities should be fed to the hot section of the kiln, e.g. the kiln inlet. To avoid enhanced dust circuits in the kiln line, the feeding of coarse particles to the kiln inlet, for example shredded material, should be preferred to pulverised material. The volatilisation of chemically bound water and of the organic compounds of the fibres at high temperatures will probably lead to the disintegration of coarse particles.

3.3 Fibre cement material affecting the clinker burning process

3.3.1 Modelling study and scenarios

In order to quantify the influence of the use of fibre cement products as a substitute for conventional raw material for clinker production a computational process engineering model developed by the Research Institute of the Cement Industry was used. Essentially it describes the process from the kiln feed input to the clinker output from the cooler [6]. The results of the calculations are comprehensive process variables, the specific energy requirement for burning the clinker as well as clinker composition.

The starting point describes a kiln plant with an energy consumption of 3 445 kJ/kg clinker at a production capacity of

Table 2: Modelling scenarios

Scenario	**1.1**	**2.2**	**2.4**	**2.5**	**3.4**
Type of fibre cement product	Exposed	Non-exposed	Non-exposed	Non-exposed	Exposed
Substitution ratio (LOI-free base) [%]	1	5	15	20	15
Fibre cement material/clinker ratio [kg/t]	16	73	220	292	228
Feeding location	Preheater	Kiln inlet	Kiln inlet	Kiln inlet	Kiln inlet

Table 3: Kiln feed composition for the different scenarios (all ratios expressed free of LOI)

Component	Unit	Reference	Scenario				
		ref	1.1 1)	2.2 2)	2.4 2)	2.5 2)	3.4 2)
Total kiln feed composition							
Substitution ratio by fibre cement production residues	%	0.0	1.0	5.0	15.0	20.0	15.0
Ratio of conventional corrected kiln feed	%	100.0	99.0	95.0	85.0	80.0	85.0
Conventional kiln feed composition							
Common kiln feed	%	100.0	97.9	88.6	67.3	57.2	67.8
High-grade limestone (Ca source)	%	0.0	0.8	4.7	13.1	16.8	12.8
Clay (Al/Si source)	%	0.0	0.2	1.1	3.3	4.4	3.3
Cinder (Fe source)	%	0.0	0.1	0.1	0.3	0.4	0.1
Sand (Si source)	%	0.0	0.0	0.5	1.0	1.2	0.9

1) Conventional raw meal mixed with fibre cement productuion residues is fed to the top cyclone stage of the preheater
2) Fibre cement production residues are fed to the kiln inlet

3 000 t/d. The kiln has a five-stage cyclone preheater, a calciner with tertiary air duct and a grate cooler. The fuel input is divided into 70 % alternative fuels (mixture of solid recovered fuels, dried sewage sludge and animal meal) and 30 % coal. Around 60 % of the fuel input is supplied to the calciner firing and the residual fraction to the main burner in the rotary kiln. On the basis of this operating condition (reference condition), numerous variations were simulated with different substitution ratios and compositions of fibre cement products. By a step-by-step increase of the substitution ratio as listed in ❱ Table 2 the maximum amount of fibre cement production residues which can be processed in the clinker manufacturing was identified.

Each scenario was compared with the reference scenario and evaluated regarding process operation. The model calculates the stationary operating conditions for each scenario as found under optimal conditions with a brief performance inspection of the reference plant. A comparison with the reference scenario is only reasonable if certain requirements such as sintering temperature, the degree of decarbonation in the hot meal in the kiln inlet, and clinker quality are fulfilled. To meet the respective target values some process parameters like the total fuel input have to be modified.

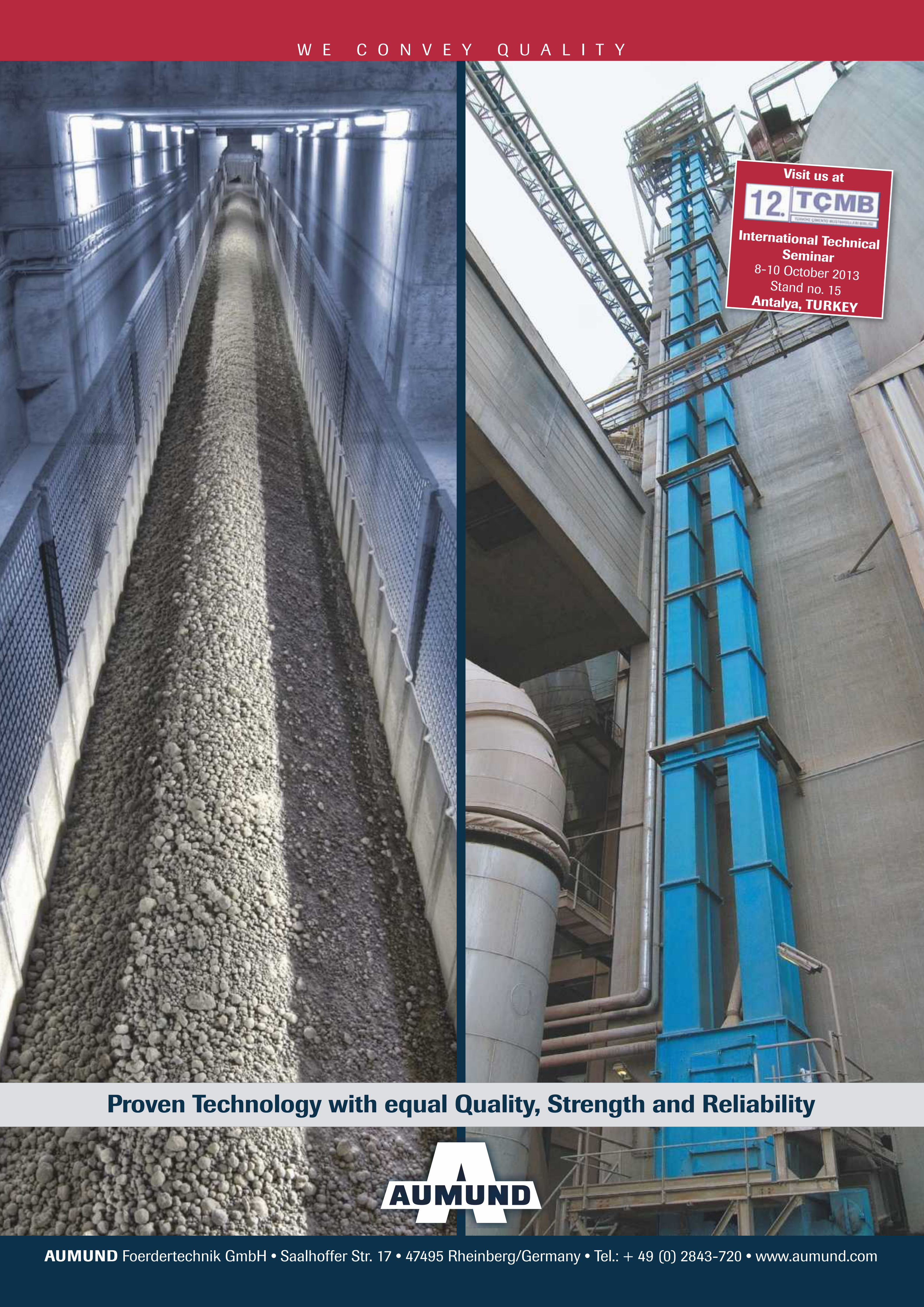
The process model operates with an average kiln feed composition representing a common kiln feed. This kiln feed is blended with non-exposed and exposed fibre cement production residues. For quality reasons regarding the cement clinker produced, the kiln feed composition can vary only within a narrow range. Therefore, the mixture composition is approximated to that of the common kiln feed by adding corrective materials (❱ Table 3). Typical compositions of a high-grade limestone as a calcium source, clay as an alumina and silicon source, cinder as an iron source, and quartz as a silicon source were used as corrective materials. To compensate the lower calcium oxide content in the fibre cement materials compared to the average kiln feed, large quantities of a calcium source are particularly required.

3.3.2 Clinker phase formation

The process model calculates the clinker phases on the basis of reaction kinetics and considers residence time and thermal profile in the rotary kiln. Despite approximately stable chemical compositions of the kiln feed, the free lime content in the clinker, which can impair the cement properties, increases slightly with increasing fibre cement material input. A maximum acceptable content of free lime is reached at 15 to 20 % substitution ratio. Regarding the clinker formation reactions there is no difference between using non-exposed and exposed material, as the LOI-free composition of both types of fibre cement products is quite similar. For reaction reasons this also applies to the other examined substitution ratios. The free lime content may possibly be higher with higher ratios for exposed materials as the rotary kiln has to yield more calcination.

The clinker phase composition in particular makes a difference with respect to the properties of the later cement such as the strength development and compressive strength. The modelling study shows differences in the phase composition of the produced clinker although the lime saturation factor, and the silica and alumina ratio are equivalent and the sintering temperatures are sufficient for optimal phase formation. ❱ Figs. 7 and 8 illustrate the formation of the clinker phases on the basis of the initial reactants and intermediate phases. The ratio between alite and belite is slightly changed and the free lime content is increased with higher fibre cement material input due to a retarded conversion compared to the reference case. Even though the material entering the kiln immediately forms more belite (upward arrow) due to the higher supply of readily calcined material than in the reference case, the reaction to the alite phase starts later in the kiln (horizontal arrow). Based on this, the reaction is less advanced at the kiln outlet, which results in higher free lime contents.
In principle this circumstance could be traced back to three major influences which interfere with each other:

- Modification of process parameters: Due to the adjustments of process parameters the temperature profile in the kiln and the heat transfer mechanisms are shifted towards the kiln inlet in the scenarios using fibre cement products residues. For this reason the tendency to form the clinker phases is impaired with increasing fibre cement material use, but can be compensated by adjusted burning conditions.



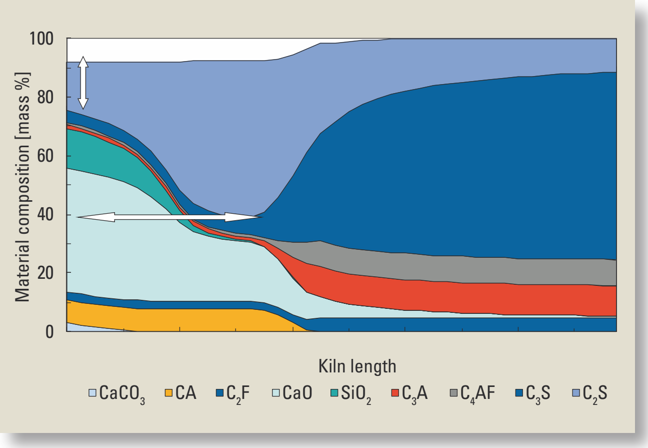


Figure 7: Clinker phase formation in the kiln of the reference case

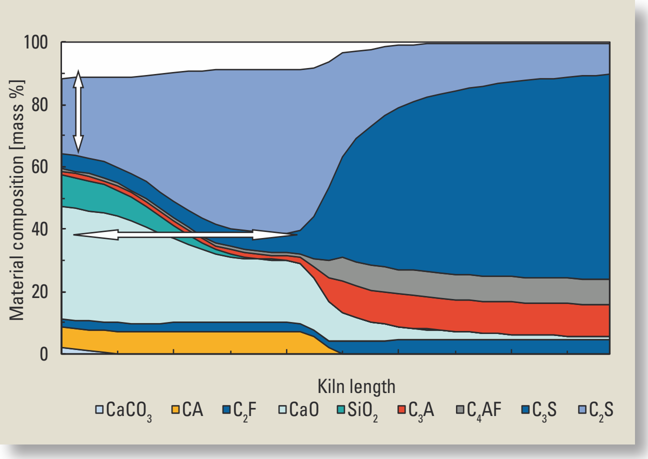


Figure 8: Clinker phase formation in the kiln by use of 20 % non-exposed materials (calculated on a LOI-free basis)

- Different amount and distribution of bound fuel ashes due to the adaptation of the fuel energy demand: In particular a reduction of the fuel input in the calciner results in lower contents of silicon, aluminium and iron in the material in the kiln inlet and therefore leads to a modified intermediate phase composition. The final product contains more alite and free lime as silicon is absent to form higher rates of belite.
- Higher sulphur content in the fibre cement materials compared to the common kiln feed: This content provokes that calcium oxide is to a higher extent bound to sulphur, which is then not available for the formation of clinker phases. As soon as the temperatures are high enough for the decomposition of the calcium sulphate the reaction of the released CaO to alite starts.

3.3.3 Kiln operation and energy input

The material based on fibre cement products adds on the one hand calcined material with low carbonate content to the process, and on the other hand it carries a high water content fixed as chemically bound water. The chemically bound water released from the fibre cement material increases the humidity of the gas flows in the kiln line and of the preheater exit gas. Water steam is a carrier of a high amount of heat due to the vaporising and overheating. As the warming-up of the kiln charge requires less energy, the gas enthalpy cannot be fully used for the process. The temperatures of the preheater exit gas rise with the increased water input of the fibre cement products. The higher the substitution of conventional kiln feed by fibre cement materials, the higher the gas humidity and the gas temperatures. Preheater exit gas temperatures rise from around 380 °C in the reference case to approx 420 and 450 °C at 15 and 20 % substitution by fibre cement material respectively, which may require an adaptation of the refractory in the preheater and exhaust gas paths.

The higher humidity and the higher temperatures of the preheater exit gas increase the energy losses in the preheater exit gas by around 140 kJ/kg clinker at 15 and 20 % substitution with non-exposed (non-carbonated) material respectively. The loss by use of 15 % exposed (carbonated) material is barely higher.

As the calcination is the most energy consuming reaction in the process, the reaction enthalpy of the kiln feed decreases substantially through use of fibre cement-based materials. The exposed samples contain recarbonated material, so the reaction enthalpy in combination with the total energy consumption is higher in comparison to non-exposed material. The reduced energy demand for the calcination results in a lower total energy consumption of the pyroprocess. The energetic benefit of the use of calcined fibre cement material is partially counteracted by the energy losses via the preheater exit gas. Nevertheless, the energy saving for calcination is higher than the increase of energy losses resulting in a total energy consumption reduction of around 300 kJ/kg clinker at a 20 % replacement. ❱ Fig. 9 illustrates the savings of the specific total energy consumption of the kiln charge of the different scenarios related to the reference case.

The pyroprocess of cement clinker manufacturing produces carbon dioxide from fuel combustion and the calcination of carbonates. The use of fibre cement production residues and product refuse lowers the carbon dioxide emissions, as carbonate-poor material is used as an alternative source. As the theoretical energy demand of the kiln feed is lower when using fibre cement materials, less fuel energy for the calcination is required. Fig. 9 displays the carbon dioxide generation for the different substitution ratios with exposed and non-exposed production residues versus the reference scenario. The exposed material is partially recarbonated and therefore offers a smaller benefit in comparison to the non-exposed material.

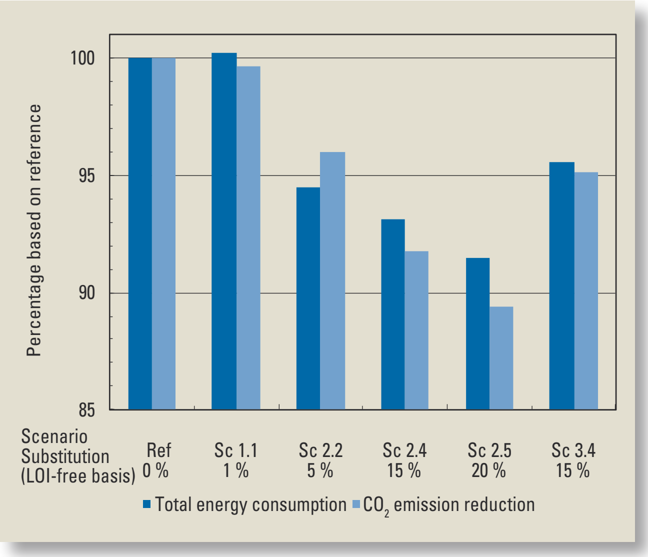


Figure 9: Savings in energy and carbon dioxide emissions due to the use of fibre cement materials. Percentage refers to the reference case (reference = 100 %).

By feeding the fibre cement-based production residues and product refuse to the kiln inlet the rotary kiln has to provide the warm-up of the material and the evaporation of the chemically bound water in addition to the sintering and the clinker phase formation. In particular the release and vaporising of the chemically bound water requires energy, while in the calciner less energy is needed for the calcination. The energy input therefore has to be shifted from the calciner to the rotary kiln firing. The use of larger quantities of fibre cement production residues of up to 20 % substitution shifts around 10 to 15 % of the thermal firing capacity of the kiln line from the calciner firing to the rotary kiln firing to provide sufficient heat for warm-up, water evaporation, sintering and clinkering.

The vaporised and overheated water carries heat from the rotary kiln to the kiln inlet. Using fibre cement production residues, the kiln inlet temperature increases from around 1 200 °C in the reference scenario to around 1 280 °C at a 15 % substitution ratio and to around 1 300 °C at 20 %. Temperatures of around 1 200 °C and higher in the kiln inlet are often observed, especially if alternative fuels are co-fired, but temperatures of around 1 300 °C may cause significant thermal stress to the refractory. So in practice, this effect would have to be counteracted by operational measures.

Clinker is blended with a sulphate agent to produce cement. Therefore, fibre cement products increase the sulphate input into the pyroprocess compared to conventional kiln feed. On the other hand, the fibre cement products have an insignificantly low chlorine content. Both compounds accumulate in the process in cycles between the rotary kiln, the calciner and the preheater. Higher contents of sulphate in the hot meal create sticky kiln charge which may form coating in the hot meal ducts. With higher contents the risk of cyclone cloggings rises.

3.4 Alternative possibilities for the use of fibre cement material in the clinker manufacturing process

Beyond the feeding of the fibre cement materials to the preheater or to the kiln inlet, two further options exist for the feeding locations of fibre cement material.

One option at calciner kiln lines is the feeding of the fibre cement material to the calciner instead of to the kiln inlet. As the material has to be carried with the up-stream gas flow, it has to be ground preferably to a meal-like fineness. The separate grinding of the fibre cement materials may require a designed grinding system due to the mechanical properties of these materials. A homogeneous mill product is required as separated phases of fibres and mineral compounds may affect the grinding system and the downstream handling. When the fibre cement material is fed into the calciner the material takes the same route as the hot meal from the cyclone stage above. As the ground material is well mixed with the conventional kiln feed, no further process changes are expected than those which occur when the fibre cement material is fed shredded to the kiln inlet. The use is limited by the kiln length due to the retarded conversion of the kiln charge to clinker.

The other option is the feeding of crushed fibre cement materials to the kiln inlet of a conventional kiln line without calciner technology. Compared with calciner lines, conventional kiln lines possess significantly longer rotary kilns. A longer residence time in the rotary kiln benefits the warm-up, drying and evaporation of the chemically bound water as well as the conversion of the kiln charge to the clinker phases. In conventional kiln lines, probably a higher substitution ratio than in a calciner line might be achieved. The substantial increase of humidity may lower the kiln performance significantly, as usually the amount of gas flows limits the production capacity.

4 Operational experience in using fibre cement production residues in the clinker manufacturing process

As of 2011 at least two cement clinker plants in Europe are using fibre cement production residues as alternative raw material. First trials were conducted with scrap plates which were fed together with limestone directly to the hopper of the crusher. As the crusher is not designed for the size, hardness and tensile strength of fibre cement products, the crusher simply smashed the plates and big pieces passed the crusher unfractured. The downstream equipment is designed for gravel, so the big pieces caused trouble and damage in the further handling. Today, the fibre cement production residues are shredded off-site down to particle sizes of up to 50 mm for smooth handling.

In one plant the hot gases from the rotary kiln are fed to the raw material crusher for drying purposes. After the crusher, no further drying of the material takes place, so the mill atmosphere is simply warmed by the heat generated by the grinding process. The residues contain moisture ranging between 12 and 15 mass % due to seasons and weather. In this plant, the moist fibre cement production residues are blended with the material flow conveyed to the raw mill. With higher moisture contents, less material can be fed to the mill to attain appropriate moisture content in the mill product for the further handling. The throughput of the raw mill is thus limited by the moisture of the mill feed. The latter is dominated by the moisture contained in the fibre cement production residues.

The residues are either blended with the natural resource in the quarry or mixed to the mill feed before the raw material grinding. After mixing the fibre cement production residues with the conventional kiln feed, the residues take the same way through the process as the conventional material. The used quantities are relatively low and less than 0.4 % of the conventional material. The small particle sizes and the low substitution ratio do not affect the material handling, the mill and kiln operation, process conditions or the clinker quality. Up to today no further kiln feeding points for the residues have been tested.

Based on a substitution ratio of 0.4 % an increase of volatile organic compounds of 5 to 10 mg/m^3 is possible. This range is in the usual spreading of emissions due to natural raw material fluctuations. Therefore, in daily operation a substitution of conventional kiln feed up to approx 1 % can be achieved if the fibre cement material is blended to the kiln feed and fed to the preheater.

Both plant operators have not determined any effects on the downstream material handling, burning process or the clinker quality by the use of fibre cement production residues, nor could process problems and changes be traced back to the use of production residues. An increased wear or failure of machinery was not observed by using the residues. The quantities used and the substitution ratio are however quite low and both operators recommend a careful investigation of the effects on material handling, the clinker burning process, product quality and machinery when using higher amounts.

5 Potentials and limitations of the use of air-cured fibre cement materials in cement clinker manufacturing

In this study the following results concerning the potentials and limitations of the use of fibre cement residues as a raw material substitute in clinker manufacturing were achieved. The comparatively low calcium oxide content in the production residues versus conventional resources requires an adjustment in the formulation of the kiln feed. With respect to the chemical main constituents, there is hardly any limitation of the fibre cement material proportion when blending the conventional resource with pure corrective materials. While the material chemistry allows quite a high portion of fibre cement material in the kiln feed, kiln operation and emissions constrict the potentials of fibre cement material use:

- Organic compounds may be released from the synthetic organic fibres and cellulose which volatilise during the preheating and calcination of the raw materials. The input of the fibre cement material blended with the kiln feed and fed to the preheater is therefore limited to less than 1 %. Higher quantities can only be achieved by feeding the fibre cement material to the hot section of the kiln, e.g. the kiln inlet, where high temperatures and long residence times destroy the fibres completely.
- The input of the fibre cement material to the kiln inlet provides a high potential of up to 20 % substitution ratio (referred to a LOI-free basis). This high use causes a considerable change of the temperature profile in the entire kiln line, and a significant heat and energy shift from the rotary kiln to the calciner and preheater affecting the conversion of the kiln charge to clinker in the rotary kiln. Limited rotary kiln length and residence time result in a less advanced conversion to clinker at the kiln outlet along with higher free lime contents. However, it can be stated that to attain a high product quality a replacement of the natural resource by fibre cement products, substitution levels up to 20 % are feasible. Potentially higher ratios can be achieved in conventional kiln lines instead of calciner plants. However, higher ratios are compensated by a considerable decrease of the kiln throughput.

As fibre cement products consist of calcined material, less carbon dioxide is generated from the raw material as well as from fuels due to reduced energy demand. At a substitution ratio of 20 % a total carbon dioxide saving from decarbonation and from fuel combustion of around 10 % is achieved. As less energy for the calcination is required the total energy demand for Portland cement clinker manufacturing is lowered by around 300 kJ/kg clinker.

Up until 2011 fibre cement production residues have only been used in a few cement plants in Europe in small quantities as an alternative raw material. The residues replace less than 0.4 % of the conventional material fed to the preheater. For smooth handling the material is reduced down to particle sizes smaller than 50 mm. This size and the low substitution ratio do not affect material handling, the mill and kiln operation, process conditions or clinker quality. Total organic emissions and the moisture content in the fibre cement production residues limit their use.

Fibre cement production residues and product refuse are valuable substitutes for raw material for Portland cement clinker manufacturing. Due to organic emissions caused by the fibre cement material it should preferably be added to the kiln inlet. Process conditions and clinker quality limit the substitution ratio of this material to 15 to 20 %.

Today retrieved fibre cement materials originate from residue of the production of fibre cement applications. In the future a return of fibre cement-based material from refurbishment and demolition of buildings is expected. The reuse of the fibre cement material as a raw material substitute fulfils the requirements of sustainability. The cement industry can contribute to an environmentally friendly recycling of these materials.

The cement industry is playing a more and more important role in waste management by using waste-derived alternative resources as a substitute in order to save natural resources. The development of environmental legislation concerning carbon dioxide control, energy efficient kiln operation, unchanged and stable product quality, and last but not least economic aspects are nowadays setting the boundary conditions. The use of fibre cement materials from production residues or from the product refuse of refurbishment and demolition waste as a substitute material in the clinker manufacturing process may contribute to meeting these challenges. ◂

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