

Rotary Drum Furnace to Investigate the Performance of Refractories for Cement Rotary Kilns

R. Simmat, C. Dannert

Fabrication processes in cement rotary kilns change due to increased utilisation of alternative fuels, and the demands on refractories change with them. Refractory manufacturers respond by developing new and improved refractory materials. With the aim to support such development actions, a laboratory rotary drum furnace test was established in order to approach industrial clinker production as close as possible, with well-defined thermal and corrosive conditions. Using a multichannel burner system, synthesized fuel residues can be added to simulate the combustion of alternative fuels.

Besides chemical corrosion by raw meal and fuel residues, the infiltration of clinker melt can now be investigated under more realistic conditions compared to standard test methods. In addition, the formation and stability of coating layers can be studied.

1 Introduction

In Germany alone, 23 Mt cement clinker are being produced in rotary kilns annually [1]. The production process of cement clinker relies heavily on refractory linings that protect the structure of the rotary kiln from the hot clinker and hot gases in the kiln itself. Refractory lining materials in cement rotary kilns degrade by a complex combination of chemical, thermal, thermomechanical and tribological loads, to name the most important. The combined interaction of these loads is most severe in the sinter zone of the rotary kiln, where at temperatures of 1450 °C the cement clinker is sintered in the presence of a clinker melt.

Demands on refractories in cement rotary kilns become stronger by increasing use of alternative fuels, which is driven by the sustained need to reduce the emission of CO₂. In Germany, the proportion of alternative fuels reached 63 % in 2014 [1]. Ashes of alternative fuels contain abundant clinker components (SiO₂, CaO, Al₂O₃, Fe₂O₃), so that using alternative fuels is an efficient way of waste utilisation. On the other hand, said components and other fuel residues are being assimilated by the clinker, where

they have an effect on the viscosity of the clinker melt and thereby its capability to infiltrate the refractory lining. Increased infiltration would accelerate corrosion of the refractories and in general reduces their thermomechanical strength [2]. The physical-chemical properties of the clinker melt also affect the formation of a stable coating layer [3], which is required on the surface of the lining in the sinter zone of rotary kilns. The coating layer protects the refractory lining against very high temperatures, excessive infiltration, thermal shock and tribological wear.

Components of alternative fuels and their residues, like alkali salts, which are volatile at the high temperatures in the sinter zone, condensate again in cooler sections of cement rotary kilns, including pores or gaps within outward parts of the refractory lining of the sinter zone. In this case, the brittleness of refractories can increase, making them more sensitive to thermomechanical stress and subsequent spalling [2]. Alkali salts from alternative fuels may also react with Al₂O₃-SiO₂ refractory components to form alkali aluminosilicate minerals, damaging the refractory lining because of volume expansion [4].

2 Scale of the problem

A typical service life of twelve months is expected from the lining of cement rotary kilns [5], independent of the type of fuel being used. Manufacturers of refractories strive to increase the performance of their products by continuously optimising existing solutions and developing new solutions. In this regard, standardised laboratory testing methods like cup corrosion/infiltration test, thermal shock or mechanical strength tests support the understanding of the behaviour of refractories under one clearly defined load.

It is clear that the performance of refractories in cement rotary kilns depends on more than one load at a time and is related to the process. Field testing of refractory products would yield most informative results, but is not undertaken due to the risk of premature failure of the rotary cement kiln lining and the associated costs.

Though the generation of adequate test conditions is a difficult task, more sophisticated methods to evaluate the behaviour of refractories under combined influence of different loads concurrently are more and more available. Using these methods, the complex situation in industrial processes is being approached in the laboratory and valuable feedback about the performance of refractories becomes available to manufacturers and R&D centers for their optimisation.

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Fig. 1 Dynamic laboratory rotary drum furnace



Fig. 2 View into the dynamic laboratory rotary drum furnace at 1450 °C with clinker nodules inside



Fig. 3 Laboratory rotary drum furnace after 8 charges of raw mix had been fired to clinker

3 Approximating the complex combination of loads in a dynamic laboratory rotary drum furnace

To simulate the combined wear of refractories in cement rotary kilns, a laboratory rotary drum furnace (Fig. 1) was set up at Forschungsgemeinschaft Feuerfest e.V. in the European Centre for Refractories (ECREF) [6, 7]. It is especially suited for investigating the effects of alternative fuel combustion on the performance of refractory linings. A multichannel natural gas/oxygen burner with a feeding system allows incorporating synthesized alternative fuel residues into the burner flame and thus simulates the combustion of alternative fuels. The hot and partially vaporised fuel residues interact with the clinker and the refractory lining of the laboratory furnace. By controlling the temperature of the burner, different temperature zones can be simulated in the laboratory furnace, like for example the sintering zone (1450 °C) or the transition zones ($T < 1450$ °C). The temperature of the flame, and the clinker are controlled by thermocouples within the rotating drum using wireless data transfer. With a flame temperature of about 1700 °C, the clinker temperature is adjusted to 1450 °C, which are the typical temperatures for clinker production in the sintering zone (Fig. 2).

After several charges of raw mix are being burned to clinker in the laboratory furnace in one-hour intervals, a coating layer is

being formed on the surface of the refractories. The coating intensity was found to depend on the raw meal composition, the amount of fine fraction of the raw meal and the kind of refractory.

A typical situation after burning cement clinker (eight charges of 1 h each) is shown in Fig. 3. Here, the clinker formed a coating layer that covered most of the refractory surface, as it happens in the sinter zone of industrial rotary drum furnaces. Rounded clinker nodules can be seen lying on the left side of the drum.

After photographic documentation of the drum situation, the test specimens are investigated for adhering mechanisms of the coating and for infiltration of clinker melt into the refractory, using SEM.

At the back end of the rotary drum furnace, hot gases are transferred into a second testing chamber, where their temperature is still about 950 °C. In this chamber, the hot gases including volatiles like alkalis and other components from the rotary drum furnace atmosphere interact with refractory insulating materials, which are used as insulating layers in cement rotary kiln linings. As the raw meal is burned to clinker on a charge by charge basis, circulation of volatile elements in the laboratory rotary drum furnace and countercurrent flow of hot gases and raw meal are not being accomplished. However, the focus of the laboratory furnace is to examine general interaction between process and refractory linings like formation of a coating, which is being achieved.

4 Results and discussion

With the help of the dynamic laboratory rotary drum furnace, the formation of clinker, the development of the coating layer on the refractories and the interaction with refractories has been studied with a number of different raw meals, refractories and furnace set-ups [6].

Exemplary results from a drum that had been lined with a magnesia-spinel refractory are discussed below and show that, when clinker is being formed, a coating layer is generated by a mechanism evolving the clinker melt, similar to the industrial mechanism of coating formation [3].

In this case, approximately 2 kg of a synthesized raw meal (R1, composition see Tab. 1) were burned to clinker. Two additional charges of R1 were then fired, now accom-

panied by the addition of a synthesized alternative fuel residue (A1, composition see Tab. 1). The components SiO_2 , CaO , Al_2O_3 and Fe_2O_3 (clinker components), which usually make up the major part of alternative fuel residues, were not included in A1 because these components are already major components of the raw meal. After the trial, samples of the clinker and the coating layer that formed on the surface of the refractory were prepared for chemical and mineralogical analysis

4.1 Formation of clinker in the dynamic laboratory rotary drum furnace

The chemical compositions of the synthesized raw meal, the clinker taken from the furnace after testing without and with addition of synthesized alternative fuel residue and the coating after tests with the addition of synthesized alternative fuel residue are given in Tab 1.

It turned out that the compositions of clinker and coating are nearly identical. The alkali contents tend to zero, indicating that the alkali cations from the synthesized raw mix became volatile during the firing and were not incorporated into clinker or coating.

After additionally incorporating the alkali rich synthesized alternative fuel residue, the clinker and the coating still did not contain alkali cations. Obviously, Na^+ and K^+ from the synthesized alternative fuel residue were also volatilized and had not been incorporated into the clinker or the coating layer, even when their availability had been greatly increased. Phosphate from the residue, however, was assimilated by the clinker and the coating, thus proving the intense interaction of A1 with the clinker and the coating during the test.

The mineralogical composition of the clinker was found to be in accordance with technical clinker. Mineralogical phase analysis of the components (Tab. 2) showed that alite, belite, tricalciumaluminate (C_3A) and calceiferite (C_4AF) were formed in the dynamic laboratory rotary drum furnace as expected. Incorporation of synthesized alternative fuel ash residue (A1) did not affect the mineralogical compositions of the clinker and the coating. The coating layer formed with the same qualitative mineralogical composition as the clinker.

Tab. 1 Chemical compositions [mass-%] of the unfired synthesized alternative fuel residue (A1), the synthesized raw mix (R1), clinker (R1-K), clinker burned during addition of synthesized alternative fuel residue (R1-K-A1), and coating generated with injection of A1 (R1-C-A1)

	A1	R1	R1-K	R1-K-A1	R1-C-A1
Al_2O_3		5,79	5,33	5,74	5,62
SiO_2		21,28	23,50	22,75	22,86
Fe_2O_3		4,90	4,09	4,16	4,15
TiO_2		0,20	0,14	0,13	0,13
CaO		64,94	66,03	66,02	66,20
MgO		0,70	0,82	0,77	0,80
K_2O	38,10	1,30	<0,01	<0,01	<0,01
Na_2O	25,20	0,30	0,01	0,01	0,01
Mn_3O_4	0,00	<0,01	<0,01	<0,01	
P_2O_5	14,40	0,00	0,04	0,40	0,20
SO_3	8,10	0,60	0,03	–	–
Cl	14,20				
Sum	100,00	100,00	100,00	100,00	100,00

Tab. 2 Mineralogical phase (XRD) analysis of clinker (R1-K), coating (R1-C) clinker burned with injection of synthesized alternative fuel ash residue (R1-K-A1), and coating generated with injection of A1 (R1-C-A1)

	R1-K	R1-C	R1-K-A1	R1-C-A1
C_3S	XXX	XXX	XXX	XXX
C_2S	XX	XX	XX	XX
C_3A	X	X	X	X
C_4AF	X	X	X	X

XXX / XX / X = strong / medium / weak intensities of X-ray reflexions

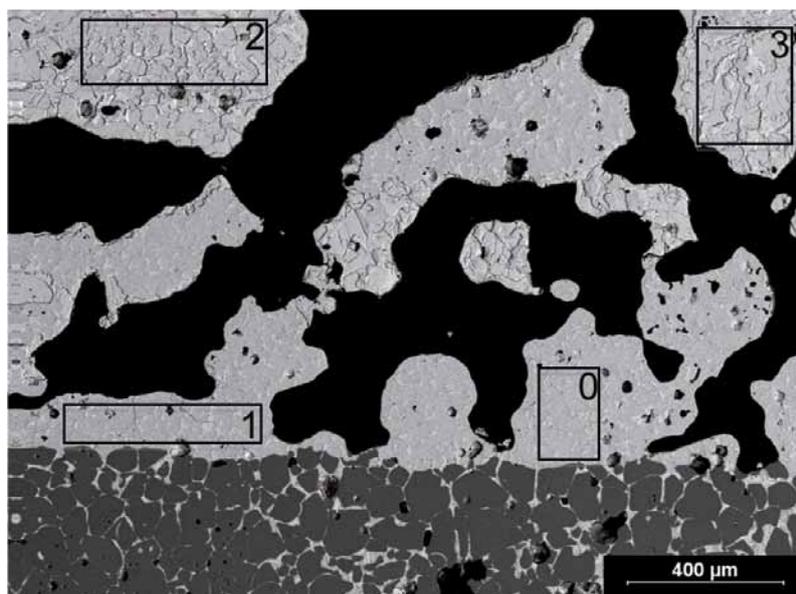
4.2 Formation of the coating layer on the refractories in the dynamic laboratory rotating drum furnace

After running the laboratory rotary drum furnace lined with magnesia-spinel brick sample specimens, a black coating layer on the surface of the refractory is clearly visible (Fig. 4). In some areas, the contact between brick and layer was weak and the layer fell off during dismantling the rotary drum.

Closer examination of the contact zones between the coating layer and the magnesia-spinell brick was carried out by SEM on polished sections. Fig. 5 shows the adhering porous coating layer on the surface of the magnesia-spinel refractory. A zoning of the coating layer was frequently observed. At the contact, the adhering aggregates looked flat compared to most of the distant aggregates with a higher relief, because they contained no alite and less ferrite. EDX analysis of areas on these ag-



Fig. 4 Surface of a magnesia-spinel refractory sample after testing at 1450 °C (scale in cm); adhering clinker (black) formed a coating layer



Oxide	Rectangle 0 Coating	Rectangle 1 Coating	Rectangle 2 Coating	Rectangle 3 Coating
Al ₂ O ₃	6,4	7,1	7,5	7,2
Fe ₂ O ₃	3,9	3,7	6,5	6,4
SiO ₂	27	26	19	19
CaO	62	62	66	66
MgO	1,5	1,6	1,3	1,5

Fig. 5 SEM electron backscattered (BSE) image of the contact area between a porous coating layer and magnesia-spinel refractory brick and results of EDX analysis

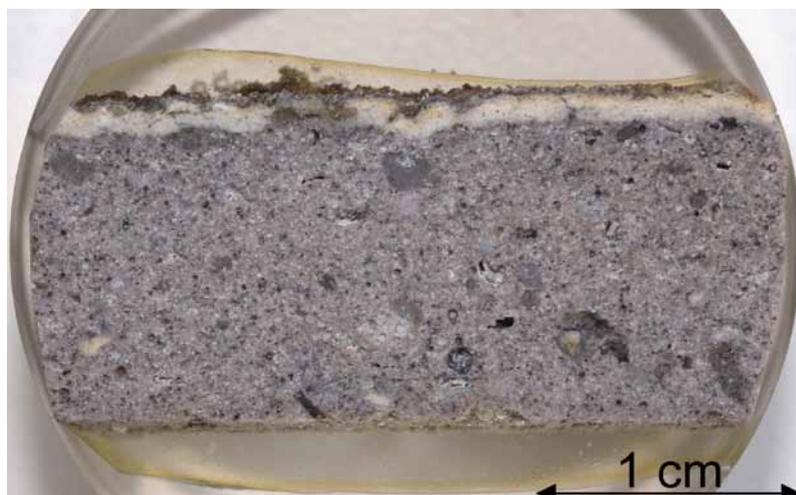


Fig. 6 Micrograph of the contact area of a fireclay insulating brick exposed to hot gas from burning clinker in the laboratory rotary drum furnace

gregates (rectangles 0 and 1) showed that they contained less Fe₂O₃, CaO and more SiO₂ compared to distant aggregates (rectangles 2, 3; Fig. 5). The authors interpreted this chemical differences as a result of the clinker melt infiltration into the refractory [6]. The clinker melt is depleted in SiO₂ but

enriched in Fe₂O₃ and CaO compared to the bulk clinker composition. The loss of melt phase also may have strengthened the rheology of the remaining clinker aggregates and intensified the contact between the refractory material and the adhering clinker. In this way, the infiltration of clinker melt

into the refractory was thought to enable the formation of the observed coating layer.

4.3 Interaction of fireclay insulating material with hot exhaust gases in the laboratory rotary drum furnace

At the back end of the rotary drum furnace, where hot gases are being transferred into a second testing chamber at 950 °C, tests were carried out with a fireclay insulating material being exposed to the hot gases that were generated in the drum furnace during the burning of eight charges of the raw mix R1 at 1450 °C. The exhaust gases interacted with the fire clay insulating material and a whitish reaction layer of about 2 mm in thickness was observed on the sample (Fig. 6).

SEM/EDX element mapping on a polished section of the sample showed (Fig. 7) that especially K₂O, but also Na₂O migrated into the porous fireclay insulating brick. At the surface, abundant CaO was found, representing dusty clinker particles. The porous structure of the insulating brick was hardly changed by the alkali elements. However, sometimes cracks were found within the alkali rich layer. The analysis of the reaction layer by XRD showed the formation of kalsilite. Obviously, a process typical for alkali bursting was beginning.

EDX element mapping of the contact zone of the fireclay insulating brick with hot gas (950 °C). Alkali cations have been deposited in a layer of about 2 mm in thickness.

5 Conclusions

In a laboratory rotary drum furnace, main effects occurring in industrial cement clinker kilns can be simulated. Incorporating synthesized alternative fuel residues into the burner flame showed that alkali metals during the clinker burning process at 1450 °C (flame temperature 1700 °C) are volatile and indicated that an increased input of alkalis, for example by alternative fuel residues, will probably not accelerate the high temperature corrosion of the basic refractories. In agreement with industrial practice, it was observed that the alkali elements migrated or were transported towards areas of lower temperatures where they took part in reactions with aluminium-silicate refractories. A coating layer consisting of clinker components built up on the refractories in

the laboratory rotary drum furnace, with mechanisms involving the clinker melt, comparable to those in industrial scale.

In agreement with industrial practice, it was observed that the alkali elements migrated or were transported towards areas of lower temperatures where they took part in reactions with aluminium-silicate refractories. At about 950 °C, typical mechanisms of alkali condensation and alkali corrosion were observed at the surface of fireclay insulation bricks that were directly exposed to the drum furnace exhaust gases. This showed that the laboratory rotary drum furnace was able to create a testing environment where also such reactions, taking place in cooler parts of rotary cement kilns, can be replicated.

The results documented the suitability of the laboratory rotary drum furnace for investigating the interactions between (alternative) fuel residue components and refractory materials, clinker and coating along a temperature gradient that is typical for industrial cement rotary kilns.

The operational conditions of the test device can be adjusted (temperatures, duration, compositions of raw mixes and fuel ashes, refractory materials...) in order to investigate special conditions in industrial applications.

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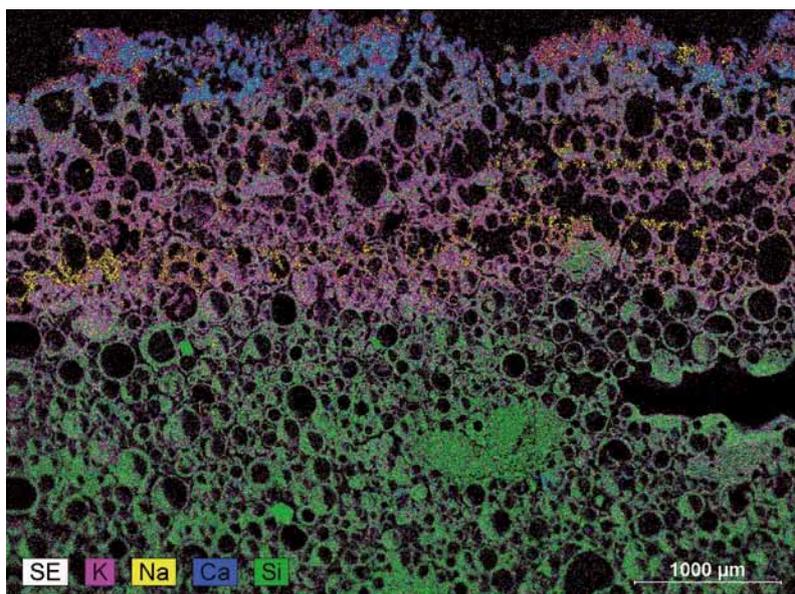


Fig. 7 EDX element mapping of the contact area between a fireclay insulating brick and hot gases from burning clinker in the laboratory rotary drum furnace at about 950 °C; alkali cations have been deposited in a layer of about 2 mm in thickness

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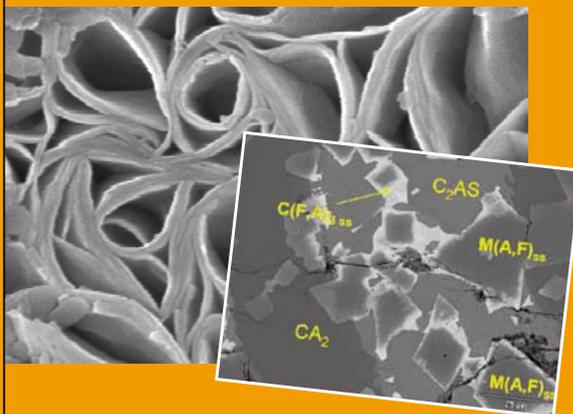
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