ECO-TAB® – A NEW ALUMINA AGGREGATE FOR STEEL LADLE LINING

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ABSTRACT

ECO-TAB® is a new alumina refractory aggregate with lower density when compared to the globally produced Tabular Alumina T60/T64 (3.3 vs. 3.55 g/cm³). The business case for the development of this new aggregate is based on its application in a steel ladle wear lining. Two factors are relevant here. The heat capacity and the thermal conductivity of the wear lining material are important for reducing the thermal losses of steel into the refractory lining during the thermal cycling of the ladle whilst in use. With lower heat capacity and thermal conductivity of the lining, the heat losses while the ladle is empty can be reduced and accordingly the heat losses from the steel to the refractory lining later. In addition, a lower density and weight of the refractory lining enables lower materials demand and higher tapping weight of steel into the ladle when the maximum crane weight in the steel works becomes the limiting factor during the ladle campaign. Firstly, the volume is the limiting factor but with increasing refractory wear, the crane weight then becomes the new limiting factor. ECO-TAB® contributes to energy saving, capacity improvement, and reduced material consumption through lower weight of the refractory lining.

The paper discusses the material properties and application testing of the new aggregate including induction furnace slag testing and thermal conductivity.

INTRODUCTION

Tabular Alumina is known for its exceptional thermal and mechanical properties. It has high refractoriness, which means it can withstand very high temperatures without undergoing significant deformation or melting. This makes it suitable for various high-temperature applications and is therefore a very common synthetic aggregate used in a number of applications for steel making refractories such as steel ladle linings, impact pads, sliding gates, nozzles and purging plugs.

One key physical parameter for Tabular Alumina is it's density, also called BSG (bulk specific gravity). It is common knowledge in the refractory industry that the higher the density of the aggregates, the better the quality. However, for the steel ladle where a thermal cycling process is applied during emptying and refilling, the density of aggregate used in the steel ladle lining influences two key factors, the thermal and weight factors.

Thermal factor

Fig. 1 shows the temperature change in the refractory lining of a steel ladle from empty to full as discussed by Ogata et al. [1].

After emptying the ladle, the hot surface of the working lining has cooled down to 800°C, as indicated in the graph. During filling and teeming, the refractory working lining temperature increases up to 1550-1600°C, resulting in energy transfer from the liquid steel to the cooler refractory lining leading to a reduction in steel temperature.

The main reasons of heat loss in the refractory lining during standard operation of a steel ladle are heat radiation and heat storage. The radiation at the steel shell can effectively be reduced by installation of insulating refractories or optimisation of the thermal conductivity of the applied refractories.

The dashed area in Fig. 1 corresponds to the heat storage (ΔQ) as defined in equation (1).

$$\Delta Q = WC_p\Delta T = \rho VC_p\Delta T \tag{1}$$

Considering the equation above, we can conclude that a reduction of heat losses by heat storage can be achieved either by reduced density (ρ) of the working lining or by decreasing it's volume (V). W represents the weight and C_p the constant specific heat capacity.

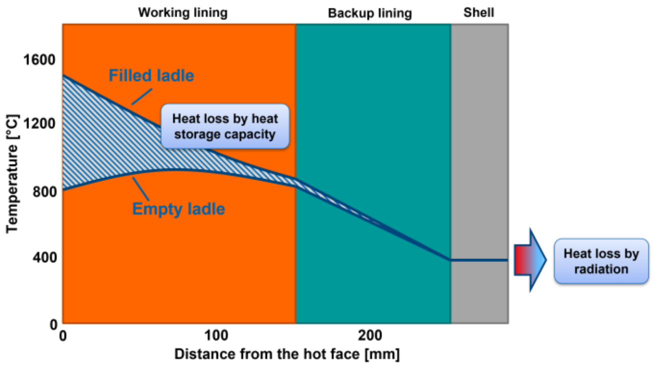

Fig. 1: Schematic drawing of the temperature change in the refractory lining of a steel ladle during operation. Drawing after [1]

Volume reduction of the working lining is often limited. A balance needs to be achieved between optimising thermal and mechanical stability whilst at the same time maximising the number of heats per ladle. The density of the refractory lining is defined by the raw materials used and the processes applied to manufacture the lining. High density raw materials are commonly used to reduce wear during application.

The costs for the loss of 1K steel temperature is considered to be in the range of 0.05 – 0.1 € per ton of steel [2]. In times of energy crisis these costs can be easily doubled.

As confirmed by Tata Steel IJmuiden [3] the costs of 1K loss per ton of steel has been €0.05. However, the current costs are expected to be in the range of €0.14 /mt steel, considering the increased energy and CO_2 prices.

Weight factor

In addition, a lower weight of refractory lining enables a higher tapping weight of steel into the ladle when the maximum crane weight in the steel works becomes the limiting factor during the ladle campaign. Initially, the volume is the limiting factor but with increasing refractory wear, the crane weight becomes the new limit instead.

ECO-TAB®

ECO-TAB® is a new alumina refractory aggregate with lower density when compared to the conventional Tabular Alumina aggregate T60/T64. The thermomechanical stability of refractory formulations is maintained at reduced bulk heat capacity leading to energy saving opportunities.

The typical physical parameters for a regular T60/T64 Tabular Alumina and ECO-TAB® are listed in Tab. 1.

Tab. 1: Typical physical parameters of T60/64 Tabular and ECO-TAB®.

		T60/T64	ECO-TAB®
Typical density (BSG)	g/cm^3	3.55	3.3
Typical apparent porosity	%	2	11
Typical water absorption	%	0.5	3.5
Al_2O_3 content	%	99.5	99.5

It is worthwhile mentioning that the lower density is not achieved by a change in chemistry but by proprietary modifications during the production process to achieve the designed microstructure. ECO-TAB® is as volume stable as Tabular T60/T64 at steelmaking temperatures.

EXPERIMENTAL

Refractory castables based on regular Tabular T60/T64 and ECO-TAB® were produced and investigated with regard to physical properties and wear resistance. Tab. 2 shows the mixture of the vibratable spinel containing castables and Tab. 3 of the vibratable spinel forming castables. In the latter, 0.5% silica fume was added to compensate for the expansion due to in-situ spinel formation.
The water demand was adjusted to achieve similar flow properties and curing of the test bars was performed at 20°C for 24h.

Tab. 2: Composition of spinel containing test castables.

	VIB-SC-TAB [%]	VIB-SC-ECO [%]
Tabular T60/T64; 0.5 – 6 mm	**55**	
ECO-TAB®; 0.5 – 6 mm		**55**
Spinel AR 78; 0.020 – 0.500 mm	27	27
Reactive Alumina	13	13
70% CAC	5	5
Dispersing Aluminas	1	1
Water demand	4.5	6.0

Tab. 3: Composition of spinel forming test castables.

	VIB-SF-TAB [%]	VIB-SF-ECO [%]
Tabular T60/T64; 0 – 6 mm	**76**	
ECO-TAB®; 0 – 6 mm		**76**
MgO; Nedmag DIN 70	5	5
Silica Fume	0.5	0.5
Calcined and Reactive Alumina	17	17
70% CAC	1.5	1.5
Dispersing Aluminas	1	1
Water demand	5.0	6.2

The refractoriness under load, thermal conductivity and induction furnace corrosion tests were performed at the German refractory institute in Höhr-Grenzhausen.

RESULTS

Microstructure investigations of ECO-TAB®

The typical microstructure of ECO-TAB® is shown on the right side of Fig. 2. The pore structure is more pronounced and finely distributed when compared to regular T60/T64 Tabular. Also, the grain size is smaller than for Tabular.
A pore size analysis was performed using the image processing software ImageJ [4] for 32 SEM images to ensure statistical value. The average pore size of 2.6 μm^2 is smaller than that of Tabular. The major difference is shown in the area of the images covered by pores. For ECO-TAB® an average of 7.2% is covered by pores, whereas for Tabular it is only 2.5%.
This optical and two-dimensional method to investigate the porosity shows a lower porosity for ECO-TAB® when compared to the bulk density (BSG) test using the normal water absorption method. However, the primary focus here was to investigate the pore size within the material.

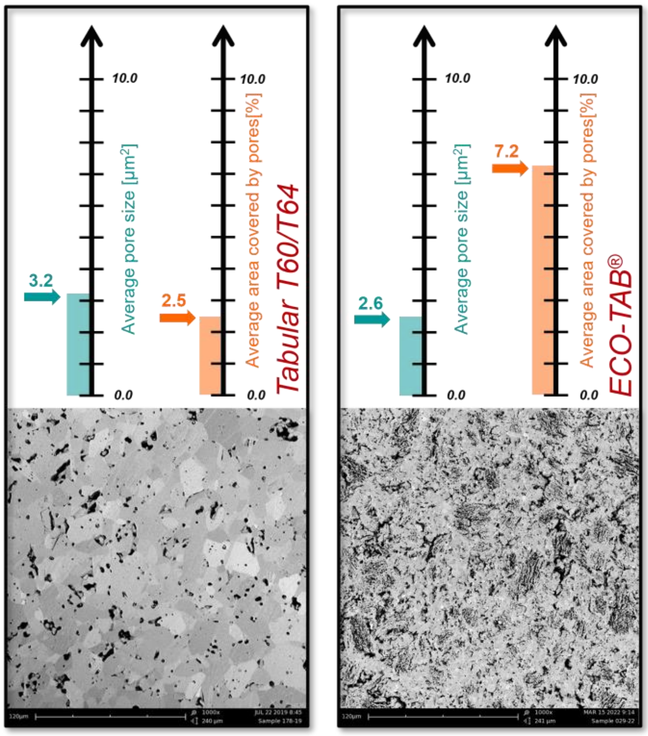

Fig. 2: Image based pore size analysis of ECO-TAB® in comparison to Tabular T60/T64. 1000x magnification.

Physical properties of refractory castables

The cold crushing strength (CCS) and cold modulus of rupture (CMoR) for the spinel containing castables is shown in Fig. 3. In the cured state (20°C / 24h) the strength for regular T60/T64 Tabular and ECO-TAB® is very similar. For the other temperatures ECO-TAB® is slightly lower in strength but still clearly exceeding the minimum level of 30 MPa CCS for steel ladle applications. Both castables show the typical drop in strength at 1000°C due to the dehydration of calcium aluminate hydrates.
Strength data for the spinel forming castables is shown in Fig. 4. Here, T60/T64 Tabular and ECO-TAB® show very similar results for all temperatures tested.
It is reported that an increase in water demand of only 1% can already reduce the strength properties by 50% [5]. Although, the water demand for the ECO-TAB® containing castables had to be increased by 1.5% and 1.2% respectively, the strength properties are not negatively affected. This can be explained by the fact that the additional water is absorbed by the higher porosity in ECO-TAB® whilst not weakening the matrix bond.

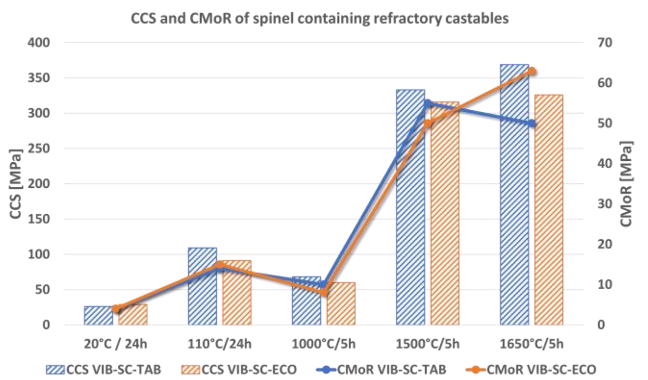

Fig. 3: Cold crushing strength (CCS) and cold modulus of rupture (CMoR) of spinel containing test castables.

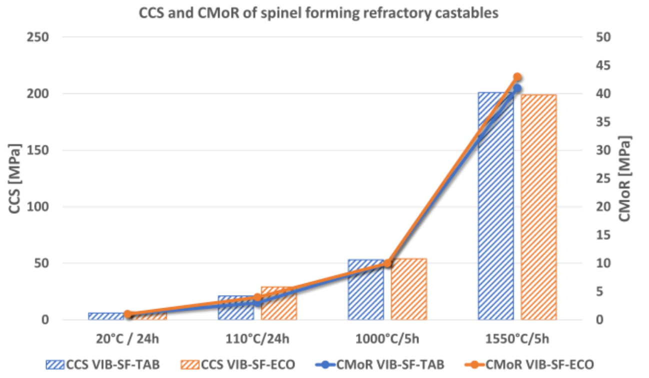

Fig. 4: Cold crushing strength (CCS) and cold modulus of rupture (CMoR) of spinel forming test castables.

The dashed bars in Fig. 5 and Fig. 6 represent the density evaluation of the dried and sintered test castables. The castables based on ECO-TAB® exhibit on average approximately 5% less bulk density (0.15 g/cm³ lower) than Tabular based castables. Fired at high temperature the difference decreases and the ECO-TAB® castables remain at ~0.1 g/cm³ lower density.

The permanent linear change as shown in the solid lines is lower for the ECO-TAB® castables, especially when fired at 1650°C or 1550°C respectively. The increased shrinkage of ~0.5% during firing is assumed to be due to the slightly increased sinter reactivity of ECO-TAB® when compared to the dense aggregate T60/T64.

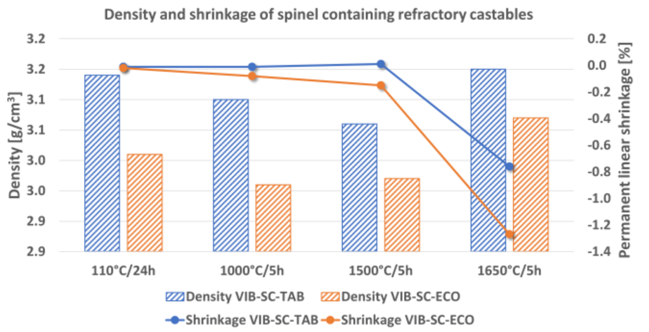

Fig. 5: Density and shrinkage of spinel containing refractory castables.

The spinel forming castables exhibit higher total positive permanent linear shrinkage due to the expansion by spinel formation during heat treatment. In addition, the castable based on ECO-TAB® shows lower expansion than the castable based on T60/T64.

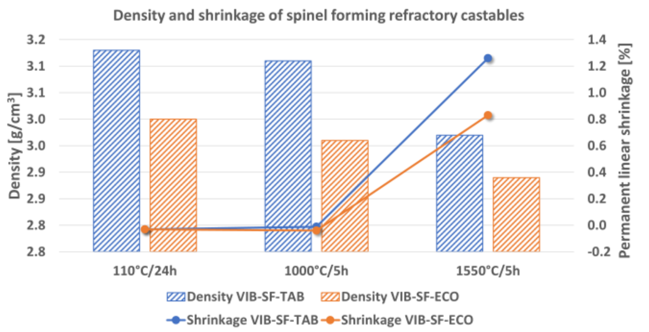

Fig. 6: Density and shrinkage of spinel forming refractory castables.

The thermal conductivity for the spinel containing test castables measured by the hot wire method is shown in Fig. 7. The castable based on ECO-TAB® exhibits approximately 10% lower thermal conductivity for the full range of tested temperatures.

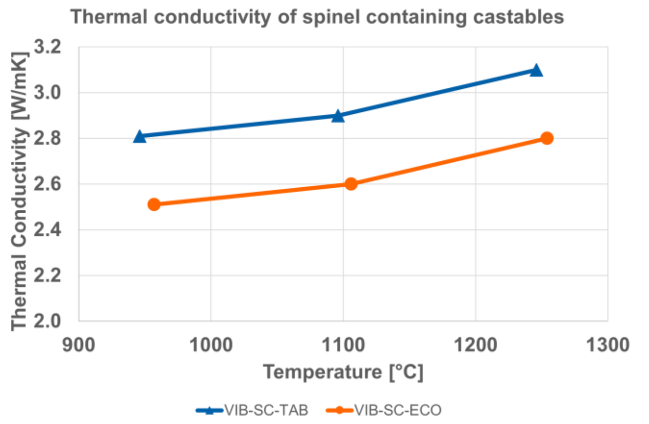

Fig. 7: Thermal conductivity for the test castables measured by hot wire method; samples pre-fired at 1000 °C / 5 h.

Refractoriness under load of spinel containing refractory castables

For the measurement of the refractoriness under load (RUL) the spinel containing refractory castable test bar was pre-fired at 1000°C with a holding time of 5h. The results for a constant pressure of 0.2 MPa and heating rate of 5 K/min are shown in Fig. 8.

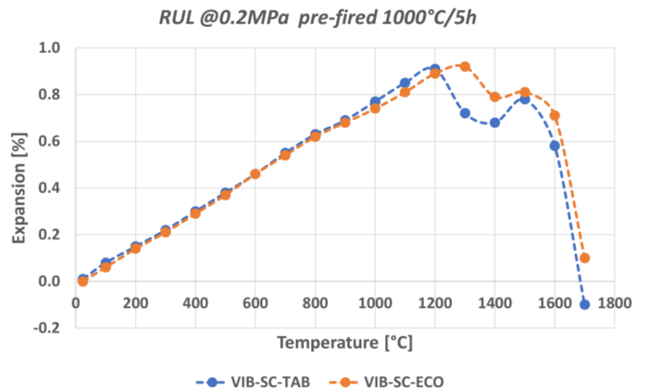

Fig. 8: Refractoriness under load of the spinel containing test castables.

The expansion curves of T60/T64 Tabular and ECO-TAB® show very similar results. The point of maximum expansion (D_{max}) is at a higher temperature (1283°C) with ECO-TAB®.

Induction furnace corrosion tests of refractory castables

In order to judge the feasibility in application, a corrosion test was conducted in an induction furnace. The test setup has the advantage of being as close as possible to real life conditions in the steel ladle. The test segments were cured at 20°C for 24h and pre-fired to 1000°C with a 5h holding time. The position of the segments in the induction furnace is shown in Fig. 9.

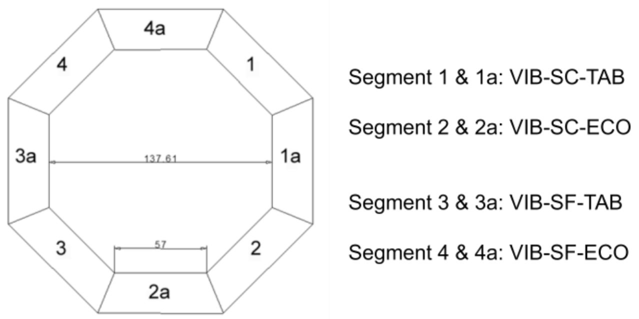

Fig. 9: Schematic drawing of segmentation for the induction furnace corrosion test.

The test was performed at 1600°C for 2h with 14 kg of ST52 steel and 750 g of a synthetic slag typical for Al-killed steel (Wt%: CaO 41.5; Al_2O_3 38.5; SiO_2 5.0; MgO 5.0; FeO 6.0; MnO 4.0). The slag was exchanged after 1 hour.
The post-mortem segments are shown in Fig. 10 and the corresponding depth of corrosion in Tab. 4. It can be seen that the depth of corrosion at the Marangoni convection zone [6] is very similar for all type of tested castables.

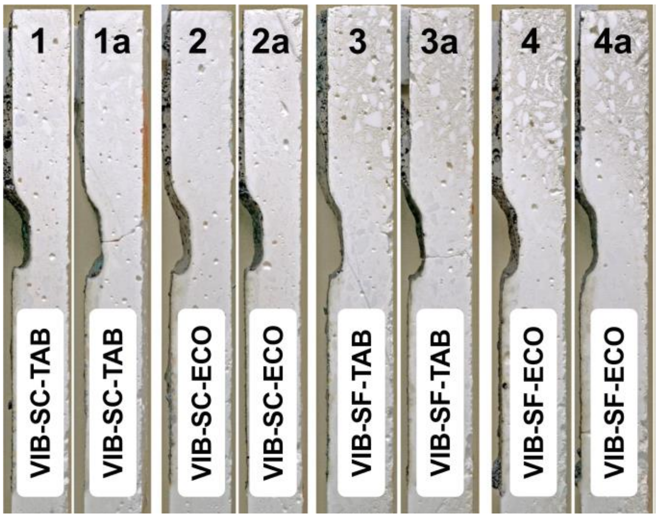

Fig. 10: Images of castable test segments after corrosion test.

Tab. 4: Depth of corrosion of tested castable segments.

	VIB-SC-TAB	VIB-SC-ECO	VIB-SF-TAB	VIB-SF-ECO
Corrosion depth [mm]	7.15	7.25	5.80	6.65

The slag infiltrated area is very visible in the polished sections as shown in Fig. 11. The dark area on the left side of each segment is remaining slag. The infiltrated area can be separated into two zones. Zone I is characterised by a brownish colour. During infiltration, the Fe and Mn content in the slag decreases leading to loss of the brownish discoloration of the refractory material (zone II). The depth of infiltrated area is very similar in the castables based on ECO-TAB® and Tabular T60/T64.
It can be concluded, that despite the significantly higher porosity of ECO-TAB®, the slag resistance of the refractory castables is very comparable.
Back scattered electron (BSE) images were taken to further investigate the reaction of the aggregate grains with the infiltrated slag. The BSE image of the area highlighted in the polished section in Fig. 11 depicts the cooled slag on the left side and infiltrated refractory castable on the right side (Fig. 12).
The solidified slag shows zonation with higher Fe contents at the hot side (white area) which remained at the surface during cooling after completion of the test.

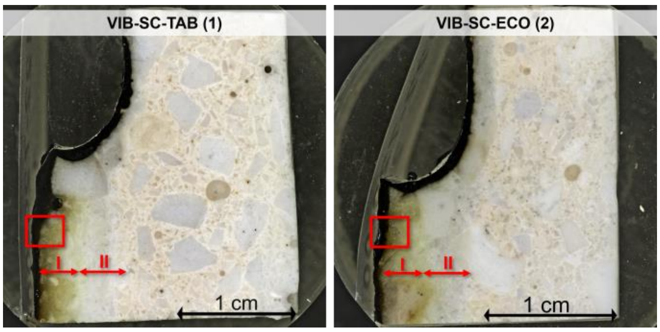

Fig. 11: Polished segments of VIB-SC-TAB (1) and VIB-SC-ECO (2) used for SEM investigations.

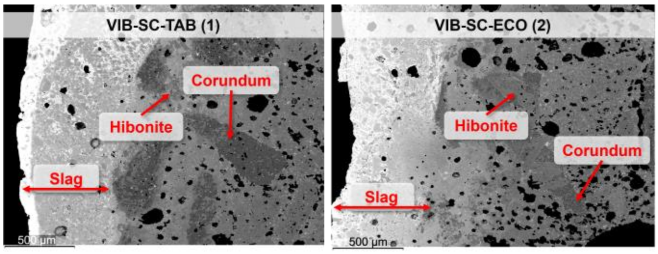

Fig. 12: BSE images of segments (1) and (2) close at the slag zone.

The fine matrix is completely infiltrated by the slag, whereas coarse alumina grains remain (dark grey phase). The Tabular Alumina T60/T64 grains in the left image show some conversion to Hibonite ($CaO·6Al_2O_3$) at the surface of the grains in contact with the infiltrated matrix (lighter grey phase). This reaction is the result of calcia availability provided by the infiltrated slag. The ECO-TAB® grains as shown on the right image show more pronounced formation of Hibonite, hence higher reactivity. However, the depth of infiltration and the resistance of the castables against corrosion is not affected.

CONCLUSIONS

This paper introduces ECO-TAB®, a new alumina aggregate with reduced density of ~3.3 g/cm³ compared to ~3.55 g/cm³ for regular Tabular Alumina T60/T64. Advantages in steel ladle linings are reduced energy losses by lowered heat capacity and thermal conductivity. In addition, the lower weight of the refractory lining enables lower material demands and higher tapping weight of steel into the ladle when the maximum crane weight in the steel works is the limiting factor.
Despite the lower aggregate density of ECO-TAB®, application tests with relevant castables show no difference in strength or refractoriness compared to the reference castable based on Tabular T60/T64. Corrosion tests reveal slightly higher reactivity of the ECO-TAB® grains in contact with slag infiltrated matrix but without any negative effect on corrosion or infiltration depth.
ECO-TAB® contributes to energy saving, capacity improvement, and reduced material consumption through lower weight of the steel ladle refractory working lining while maintaining end application performance.

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