

Report.

Research projects of the FEHS-Institute 2025

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ELECTRIC HOT METAL SLAGS FROM THE DRI SMELTER ROUTE AS A MAIN CEMENT CONSTITUENT (SAVE CO₂)

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INTRODUCTION

Current steel production in Germany is divided into 71% via the blast furnace/BOF converter route (integrated route) and 29% via the electric arc furnace route. In Europe (EU-27) these shares amount to 56% and 44%, respectively [1]. In today's European electric arc furnaces, scrap is used almost exclusively as input material for crude steel production, meaning that primary raw materials such as iron ore and coal or coke are not required. Depending on the electricity mix provided, this route can already operate with significantly lower CO₂ emissions compared to the integrated route, approximately 410 kg CO₂ per tonne of crude steel instead of 1,921 kg per tonne [2].

Technological progress has brought the blast furnace process close to its thermodynamic optimum. Even theoretically, significant advances toward climate-neutral production by 2050 are not feasible. At the same time, increasing steel production in electric arc furnaces is constrained by limited scrap availability and necessary quality requirements. For these reasons, the steel industry is focusing on the introduction of new technologies that fundamentally avoid

CO₂ emissions, referred to as Carbon Direct Avoidance (CDA).

The industrial production of cement with reduced clinker content in Europe relied for decades on the use of granulated blast furnace slag (GBFS) as a latent hydraulic main constituent. This material cycle links the steel and cement industries. Slag from the conventional blast furnace route is water granulated, ground and used as a main cement constituent, thereby significantly reducing the CO₂ emissions of the binder. With the accelerated decarbonisation of steel production through substitution of the blast furnace by hydrogen-based direct reduction (DR) and downstream electric melting processes such as smelters or electric arc furnaces, new slag types are generated. These differ in chemistry, mineralogy and process logic from established blast furnace slag. Without appropriate utilisation pathways, the raw material stream for clinker-efficient cements would decline, and the CO₂ balance of the cement industry would deteriorate.

SAVE CO2 PROJECT

The two-stage process for integrating a direct reduction plant into steel production consists of a smelter followed by a converter. When using a smelter directly downstream of the direct reduction plant, as shown schematically in Figure 1, electric hot metal and a slag are produced. Depending on the slag-forming agents used, this slag may exhibit similarities to conventional blast furnace slag.

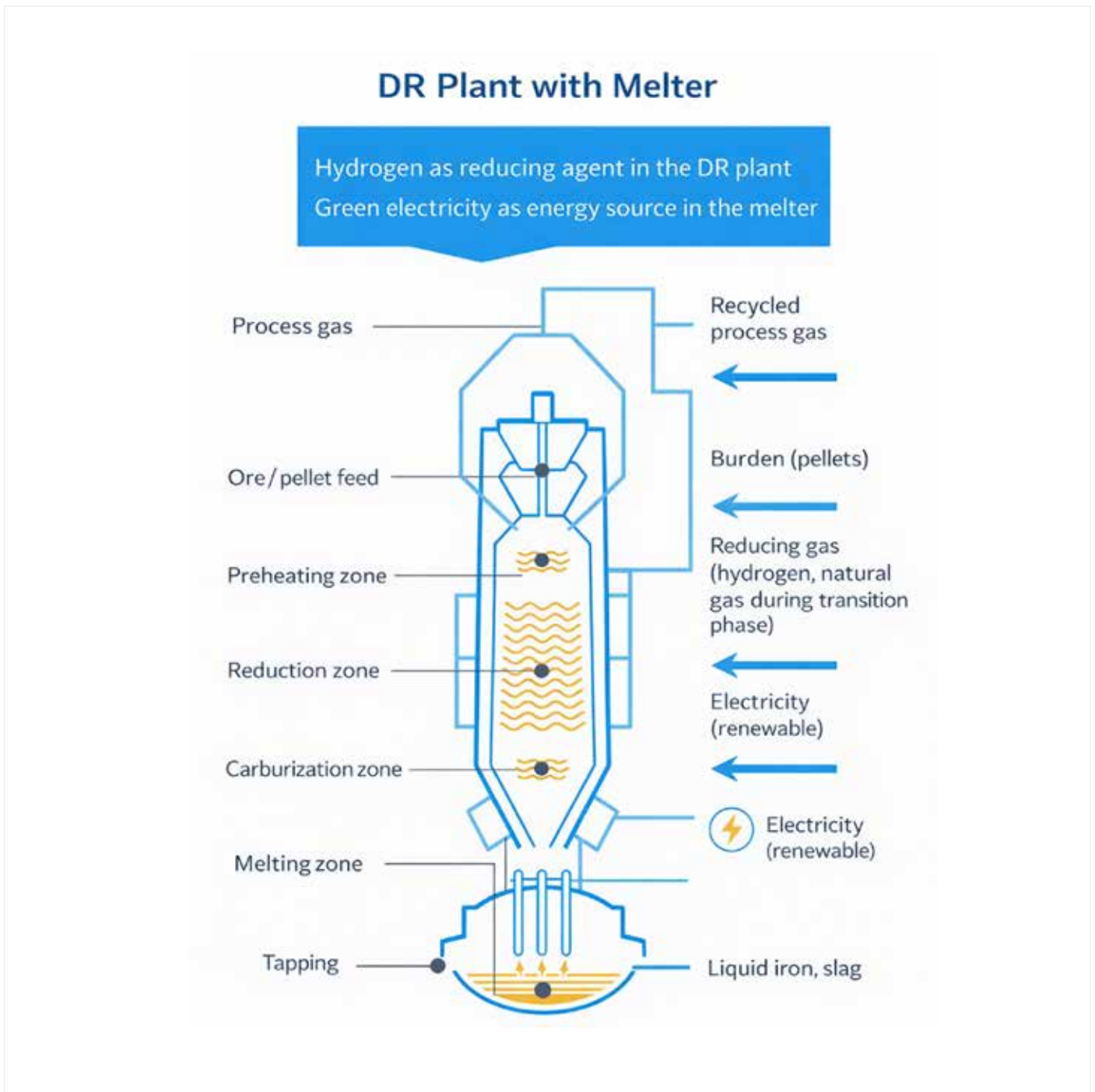


Figure 1: Schematic representation of a DR plant with smelter [4]

Investigations on this slag were the subject of the research project funded by the German Federal Ministry of Research, Technology and Space (BMFTR), "SAVE CO₂", which aimed at creating an alternative application for electric hot metal slag (EHMS) produced on a DRI basis for use in the cement industry in order to reduce CO₂ emissions [3]. While blast furnace slags have been utilised as high-quality secondary raw materials in the cement industry for decades and are comprehensively standardised, no empirical data or industrial applications previously existed for slags from DRI-based processes. Consequently, fundamental knowledge regarding the chemical and mineralogical characteristics, glass formation behaviour, environmental compatibility and hydraulic activity of these new slag types was lacking.

The project objective was to accompany the new process route consisting of a direct reduction plant and an electric smelter, to model the slags expected to be generated in the future, to produce them experimentally, to characterise them systematically and to demonstrate their suitability as a CO₂-reduced alternative to blast furnace slag.

The consortium consists of the steel producer thyssenkrupp Steel Europe, the cement producer Heidelberg Materials and the scientific partners Institute of Technologies of Metals (ITM) at the University of Duisburg-Essen and Fraunhofer Institute UMSICHT, with FEhS-Institut für Baustoff-Forschung e.V. as project coordinator.

The focus was placed on investigating the dependence of slag properties on variable input materials and process parameters, as well as on assessing the technical and economic requirements for complete material utilisation in the cement industry. The aim was to ensure that the advantages of decarbonisation in steel production would not be offset by increased emissions or disposal in the construction materials sector.

The work comprised laboratory, pilot-scale and large-scale trials, determination of chemical, mineralogical and latent hydraulic properties of the slags, as well as cement and concrete testing. In addition, environmental analyses, life cycle assessments and economic evaluations were conducted.

The research demand included both process metallurgical analysis and adjustment of suitable slag compositions and cement-technical evaluation of the resulting materials. Only through such an interdisciplinary approach could it be ensured that the decarbonisation of steel production would not lead to the loss of established material cycles between the steel and cement industries. The SAVE CO₂ project addressed precisely this interface between metallurgical process development, including viscosity and electrical conductivity, and building materials research, in order to close the scientific gap between future DRI-smelter technology and sustainable by-product utilisation.

RAW MATERIALS AND RESULTING SLAGS

Within the project, a selection of directly reduced raw materials from different regions was procured and investigated. This reflects the boundary conditions of the planned large-scale industrial plant, in which ores of varying qualities and origins are expected to be reduced.

At the beginning of the investigations, the input materials were comprehensively characterised in order to establish a reliable basis for the subsequent melting trials. Four different DRI and HBI qualities were analysed:

- Hot Briquetted Iron from Russia (HBI, Figure 2a)
- Direct Reduced Iron from Iran (DRI-I, Figure 2b)
- Direct Reduced Iron from Egypt (DRI-E, Figure 2c)
- Hydrogen-reduced Direct Reduced Iron (DRI-H₂, Figure 2d)

The samples originated from different deposits and were supplied in the form of briquettes or pellets.

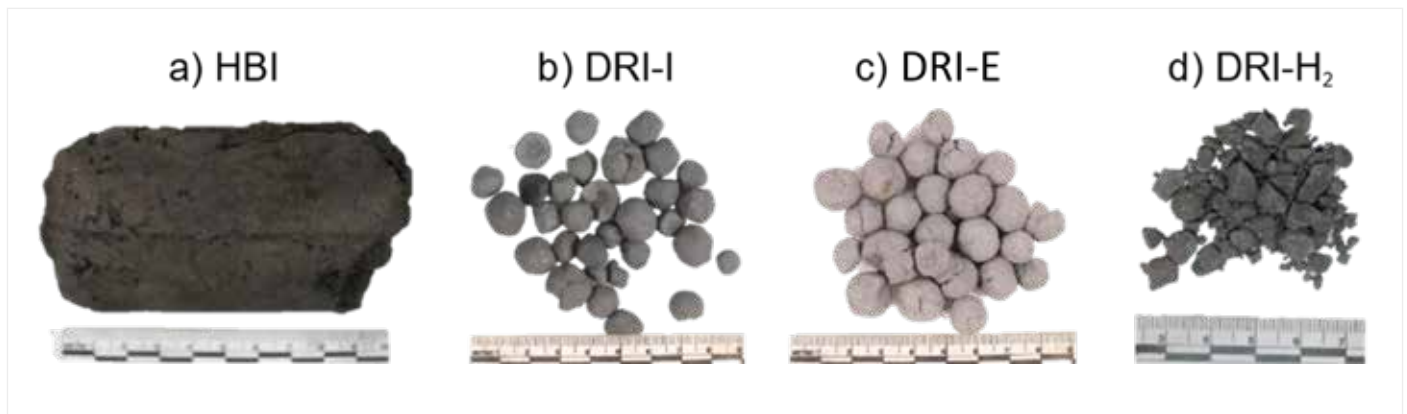


Figure 2: Initial condition of DRI and HBI qualities

Table 1: Carbon and sulphur contents of the DRI and HBI qualities investigated

[wt.%]	HBI	DRI-I	DRI-E	DRI-H ₂
C (range)	1.10–3.13	1.17–2.64	2.3–2.97	–
C (average)	1.88	1.99	2.54	0.026
S (average)	0.0020	0.0042	0.0053	0.0042

The gangue in the DRI and HBI material consisting of oxides that do not transfer into the metallic phase typically amounts to approximately 10 wt.% and forms the basis of the later slag. Of particular importance are the main oxides SiO_2 , Al_2O_3 , CaO and MgO , as well as deposit- and process-dependent minor and trace elements such as TiO_2 , V_2O_5 and alkalis. In addition, the carbon content in DRI varies depending on the respective reduction process, as shown in Table 1.

Based on the characterisation of the input materials, systematic melting trials were conducted at the Institute of Technologies of Metals (ITM) on a laboratory scale. The objective was to gain a fundamental understanding of the melting and foaming behaviour of the investigated input materials HBI, DRI-I, DRI-E and DRI-H₂.

Furthermore, the trials served to select suitable crucible materials for subsequent investigations in the electric furnace. For this purpose, induction furnaces of different capacities, 2 to 80 kg, as well as a vacuum induction furnace with batch sizes up to 5 kg, were used.

Slag chemistry and metal phase

Neutral remelting of DRI and HBI leads to the formation of slags whose chemical and mineralogical properties differ significantly from those of conventional blast furnace slags. For utilisation of these slags in the cement industry, targeted adjustment of the composition, for example through the addition of lime, is therefore required.

To determine suitable addition rates, the various DRI qualities and the HBI were first remelted under inert conditions in an induction furnace and in a vacuum induction furnace. Complementary experiments were carried out in the specially developed electric arc furnace at ITM, in which the samples were likewise remelted under neutral conditions and subsequently analysed, see Figure 3.

The slag and metal samples obtained were subjected to detailed analytical investigation. Based on these results, a calculation model was developed that considers both mass balances and typical reduction and oxidation reactions between the slag and metal phase.

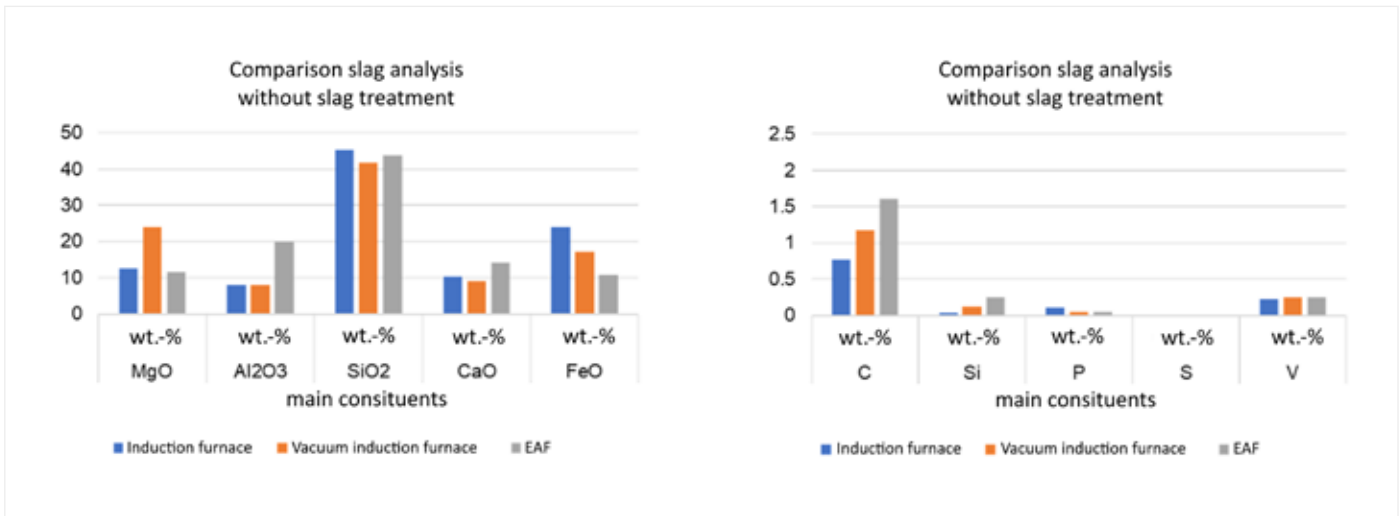


Figure 3: Comparison of slag analysis (left) and metal analysis (right) of the neutrally remelted input materials

In the ITM electric arc furnace, several conditioning trials with melt masses of up to approximately 100 kg were successfully performed. It was demonstrated that the results from laboratory-scale melting trials, approximately 1 kg, are transferable to larger melt quantities. In all cases investigated, the targeted adjustment of the slag composition could be achieved, and a slag was produced whose mineralogical phases were comparable to those of granulated blast furnace slag.

PRODUCTION OF SLAGS IN LAB SCALE

The investigation of the input materials showed that the gangue remaining in the reduced material generally exhibits a CaO-to-SiO₂ ratio (simple basicity B₂) significantly below unity, in some cases reaching values of only approximately 0.2. In this state, the material is unsuitable both from a binder-technical perspective for use in the cement industry and from a process-metallurgical perspective for steel production, particularly due to the high slag viscosity.

For this reason, an increase in basicity through the addition of lime, CaO, is required in order to achieve B₂ values typical of current granulated blast furnace slags.

In addition to the CaO-to-SiO₂ ratio, the Al₂O₃ and MgO contents also influence the suitability of the material. Targeted adjustment of these components may therefore have positive effects on product properties. However, each addition of slag-forming agents

in the melting process is associated with additional raw material costs, increased energy demand and thus additional CO₂ emissions, as well as an extension of the tap-to-tap time, the time interval between two furnace tappings.

Slag treating as a by-product thus operates within a field of tension between optimisation of material properties, costs for additives and energy, and environmental impacts resulting from additional CO₂ emissions. In contrast to this is the potential CO₂ saving achieved by clinker substitution in cement production.

Melting programme

In order to provide a basis for decision-making within this field of tension, the system boundaries were defined together with the industrial partners. The objective was to cover a realistic range of both metallurgical and process-related boundary conditions as well as the subsequent application of the slags in the cement industry.

On this basis, a design of experiment (DoE) was established that covers a broad parameter space, see Table 2, which future EHMS from the smelter may occupy depending on operating conditions, input materials and the targeted cement-technical performance, equivalent to granulated blast furnace slag.

Table 2: System boundaries of the design of experiment for the base composition of the new EHMS

Parameter	Unit	Range/ System boundary
Slag temperature	°C	1,450 (1,550) 1,650
B ₂ basicity	-	0.70 1.40
Aluminium oxide content	wt.%	6.0 (10.5) 15.0
Magnesium oxide content	wt.%	2.0 10.0

In order to investigate the variation range of the four main parameters with a sufficient yet limited number of experiments, a full factorial DoE was selected. This comprised two groups with eight experiments each as well as a connecting centre point.

In addition to the DoE, numerous further laboratory slags were produced to verify the results or, based on a second DoE, to specifically investigate the influence of TiO₂, V₂O₅ and alkali oxides. This second DoE served in particular to analyse the influence of selected minor constituents on the cement-technical properties of the electric hot metal slags.

The raw material base for direct reduction plants is expected to exhibit greater variability than in blast furnace operation, since not all iron ores are equally suitable for use in DR plants. Moreover, reduction conditions in the blast furnace are considerably more intensive, meaning that elements such as vanadium are largely reduced and transferred into the metal phase. In the DR process, however, these elements remain in the gangue and may therefore gain increased relevance in the resulting slag.

Based on the results of the first experimental series, which systematically investigated the influence of the main components, the subsequent work focused on these minor constituents, in particular titanium, vanadium and the alkalis sodium and potassium. The objective was to clarify to what extent these trace elements may negatively affect glass formation, melt homogeneity or the cement-technical suitability of the granulated material.

Within the DoE, combinations of different concentrations of TiO₂, V₂O₅, K₂O and Na₂O were specifically adjusted in order to capture both individual and interaction effects of the oxides. The main components were largely kept constant, with a B₂ basicity of approximately 1.05, an Al₂O₃ content of 10.5 wt.% and an MgO content of 6 wt.%. Target contents for TiO₂ ranged from 0 to 3.5 wt.%, reflecting the maximum concentrations expected from industrial processes. V₂O₅ was added up to 1 wt.%. Na₂O varied between 0.15 and 2 wt.%, while K₂O was adjusted between 0.15 and 3.5 wt.%.

This approach enabled a scientifically substantiated assessment of the extent to which natural fluc-

tuations of minor constituents in electric hot metal slags may influence the formation of a glassy structure and cement-technical usability.

Experimental setup: Tammann furnace and water granulation

The melting experiments were carried out using the Tammann furnace in the melting laboratory of the FEhS-Institute. This furnace is specifically designed for investigations on liquid slags and enables neutral melting of synthetic pure substances that served as starting materials for the experiments, see Figure 4.

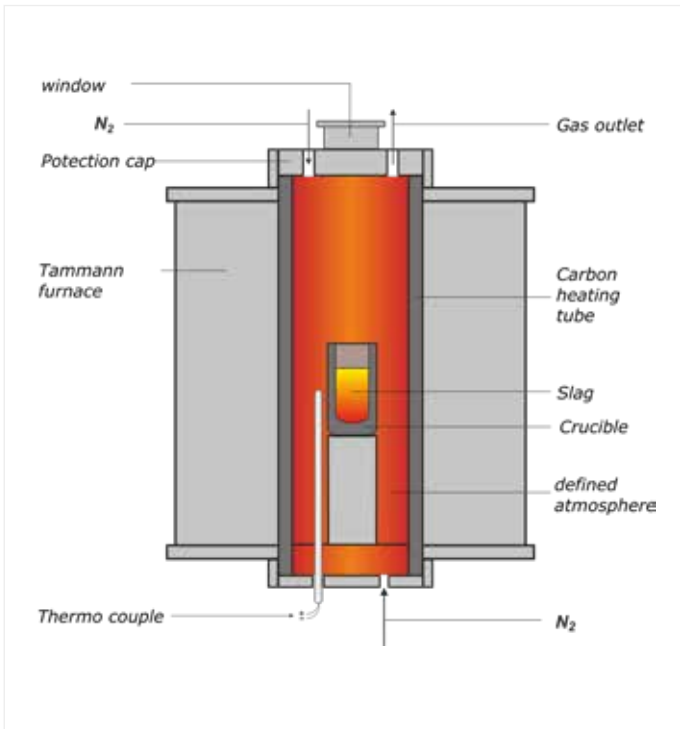


Figure 4: Tammann furnace



Figure 5: Water granulation device

For each melting experiment, 2,000g of a synthetic slag were prepared, and the respective crucible was completely filled. The target compositions were derived from the DoE. After reaching the target temperature and ensuring sufficient homogenisation of material and temperature, the molten sample was quenched in the FEhS water granulation device, see Figure 5.

Results of the melting experiments

Table 3 presents the chemical compositions and glass contents of the laboratory slags produced within the framework of the first DoE. Chemical analysis was performed in the FEhS chemical laboratory by XRF analysis on fused beads. The glass content was determined in accordance with the specifications of the metallurgical laboratory manual.

The chemical compositions determined showed a high level of agreement with the specified target values, indicating high reproducibility and stability of the experimental procedure.

The majority of the investigated slags solidified into fully glassy products with glass contents exceeding 95vol.%. Only individual melts, particularly experiments SC2-7 and SC2-18 to SC2-20, exhibited significantly

reduced glass contents below 30 vol.%. These compositions were located near the merwinite region of the $\text{CaO-Al}_2\text{O}_3\text{-SiO}_2\text{-MgO}$ system and, due to their higher basicity (B_2 approximately 1.5), showed a pronounced tendency toward crystalline solidification, which largely suppressed glass formation.

An increased aluminium oxide content generally had a favourable effect on glass formation, since Al_2O_3 stabilises the network structure of the melt and reduces crystallisation tendency. Thus, fully glassy samples could be achieved even at comparatively high B_2 basicities up to approximately 1.4, provided the Al_2O_3 content was in the range of 14 to 15 wt.%. At lower B_2 basicities of approximately 1.1 or below, complete vitrification was possible even without elevated aluminium oxide contents.

Within the investigated system boundaries, the influence of MgO remained minor and showed no clear systematic correlation with the glass content.

In summary, the results demonstrate that glass formation in DRI-based electric hot metal slags can be specifically controlled through adjustment of basicity and aluminium oxide content. Nearly complete vitrification, and thus attainment of the amorphous

Table 3: Chemical composition and glass content of the laboratory slags

Trial	Temperature		CaO		SiO ₂		C/S		Al ₂ O ₃		MgO		Glass
	target	actual	target	actual	target	actual	target	actual	target	actual	target	actual	actual
	[°C]	[°C]	[wt.%]	[wt.%]	[wt.%]	[wt.%]	[-]	[-]	[wt.%]	[wt.%]	[wt.%]	[wt.%]	[vol.%]
SC2-1	1,650	1,650	37.88	39.40	54.12	49.70	0.70	0.79	6.00	7.16	2.00	2.31	100.0
SC2-2	1,450	1,450	30.88	31.50	44.12	43.70	0.70	0.72	15.00	14.40	10.00	9.81	100.0
SC2-3	1,450	1,550	53.67	54.60	38.33	35.90	1.40	1.52	6.00	6.67	2.00	2.37	58.7
SC2-4	1,650	1,650	48.42	49.50	34.58	32.20	1.40	1.54	15.00	15.50	2.00	2.35	99.9
SC2-5	1,550	1,550	42.77	43.80	40.73	38.00	1.05	1.15	10.50	11.20	6.00	6.37	100.0
SC2-6	1,650	1,650	34.18	35.40	48.82	45.40	0.70	0.78	15.00	16.10	2.00	2.34	100.0
SC2-7	1,450	1,550	49.00	50.10	35.00	32.60	1.40	1.54	6.00	6.56	10.00	10.40	8.2
SC2-8	1,450	1,450	34.59	41.70	49.41	46.40	0.70	0.90	6.00	0.80	10.00	10.50	99.8
SC2-9	1,450	1,450	43.75	44.70	31.25	29.10	1.40	1.54	15.00	15.40	10.00	10.50	94.8
SC2-10	1,650	1,650	49.00	49.30	35.00	33.20	1.40	1.48	6.00	6.57	10.00	10.40	70.8
SC2-11	1,450	1,550	48.42	48.90	34.58	32.50	1.40	1.50	15.00	15.60	2.00	2.23	100.0
SC2-12	1,650	1,650	53.67	54.20	38.33	36.00	1.40	1.51	6.00	6.72	2.00	2.46	95.6
SC2-13	1,450	1,450	37.88	39.30	54.12	49.60	0.70	0.79	6.00	7.09	2.00	2.89	99.8
SC2-14	1,450	1,550	34.18	35.90	48.82	45.60	0.70	0.79	15.00	14.90	2.00	2.43	100.0
SC2-15	1,650	1,650	30.88	31.80	44.12	40.50	0.70	0.79	15.00	16.80	10.00	9.89	100.0
SC2-16	1,650	1,650	43.75	44.10	31.25	29.70	1.40	1.48	15.00	15.30	10.00	10.30	99.0
SC2-17	1,650	1,650	34.59	35.10	49.41	45.80	0.70	0.77	6.00	6.94	10.00	10.40	100.0
SC2-18	1,450	1,550	49.00	49.00	35.00	32.60	1.40	1.50	6.00	6.58	10.00	10.60	20.3
SC2-19	1,450	1,550	48.76	48.70	34.83	33.13	1.40	1.47	5.97	6.68	9.95	10.80	19.5
SC2-20	1,450	1,550	48.28	48.80	34.48	32.70	1.40	1.49	5.91	6.70	9.85	10.80	26.8
SC2-19-2	1,450	1,550	48.21	48.80	34.80	32.90	1.39	1.48	6.00	6.10	10.00	10.40	n.b.
SC2-20-2	1,450	1,550	46.50	49.10	34.50	32.70	1.35	1.50	6.00	6.35	10.00	10.60	n.b.

structure required for cement applications, is favoured particularly at moderate basicities in combination with elevated Al₂O₃ contents, whereas strongly merwinitic compositions should be avoided.

Minor constituents: TiO₂, V₂O₅, alkali oxides

Evaluation of the melting experiments concerning the minor constituents investigated showed that TiO₂, V₂O₅ and the alkali oxides Na₂O and K₂O had only a limited influence on the melting and solidification behaviour of the laboratory slags produced.

The addition of sodium and potassium oxide did not reveal any relevant effect on glass formation or on other chemical or physical properties. However, due to the use of carbonates as starting materials and the associated release of CO₂ during melting, the targeted concentrations could not always be adjusted

exactly, resulting in minor deviations between target and actual compositions.

Vanadium oxide likewise showed no noticeable effects with respect to glass formation or melt viscosity and had no significant influence on the cement-technical properties of the solidified and granulated slags, see Section 4.4.

In contrast, titanium oxide proved to be potentially critical, although not in the actual melting process. TiO₂ did not negatively affect the glass content or melt viscosity, but it significantly influenced the hydraulic reactivity of the binders produced from these slags. At TiO₂ contents of approximately 1 wt.% and above, a noticeable decrease in mortar compressive strength was observed, particularly in the early strength range, see Section 4.4.

Overall, the results confirm that elevated TiO_2 contents, in contrast to Na_2O , K_2O and V_2O_5 , may have an unfavourable influence on cement-technical performance, whereas the other investigated trace elements can be classified as largely uncritical.

Cementitious investigations of the laboratory slags

The laboratory slags described above were characterised according to a standardised cement-technical testing scheme of the FEhS-Institute.

Initially, the slags were ground in a closed ball mill to a defined fineness. The objective was to achieve a particle size distribution comparable to that of conventional granulated blast furnace slag at a Blaine value of approximately $4,200 \text{ cm}^2/\text{g}$ according to DIN EN 196-6.

The ground slags were subsequently blended at 50 wt.% with Portland cement CEM I 42.5 R, which fulfilled the requirements of a reference cement according to DIN EN 15167-1. These binder combinations were investigated with regard to workability, strength development and heat of hydration in accordance with the DIN EN 196 series of standards.

With respect to workability, no abnormalities were observed for the combinations containing laboratory slags.

Due to the strongly varying chemical compositions of the laboratory slags, significant differences in mortar compressive strengths were expected and were indeed observed. Figure 6 exemplarily presents the results for samples SC2-1 to SC2-17. The determined strength values were in part significantly above or below the mean values determined for the tkSE granulated blast furnace slags HS 1 to HS 4.

Irrespective of these differences, in all cases a strength exceeding that obtained with inert quartz filler was achieved after only two days of hydration, a stage at which clinker hydration dominates.

The impact of slag chemical composition on strength development follows the same fundamental relationships long known for granulated blast furnace slag. As an example, the contour diagram in Figure 7 illustrates, for two different MgO contents, the influence of Al_2O_3 content and basicity on 2-day mortar compressive strength.

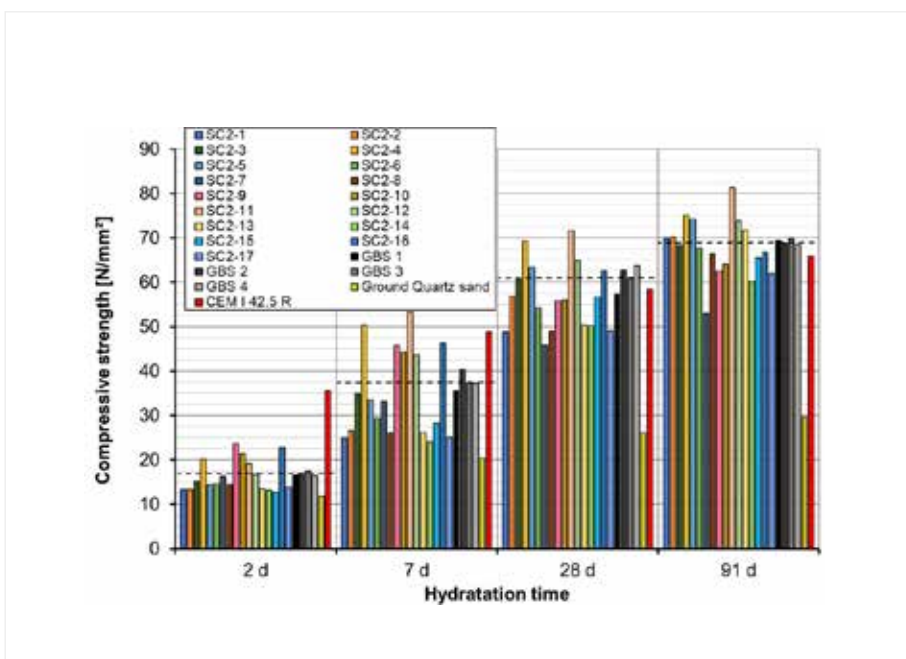


Figure 6: Development of compressive strength of mortars according to DIN EN 196-1 for combinations of 50 wt.% laboratory slag, granulated blast furnace slag and quartz filler with Portland cement CEM I 42.5 R

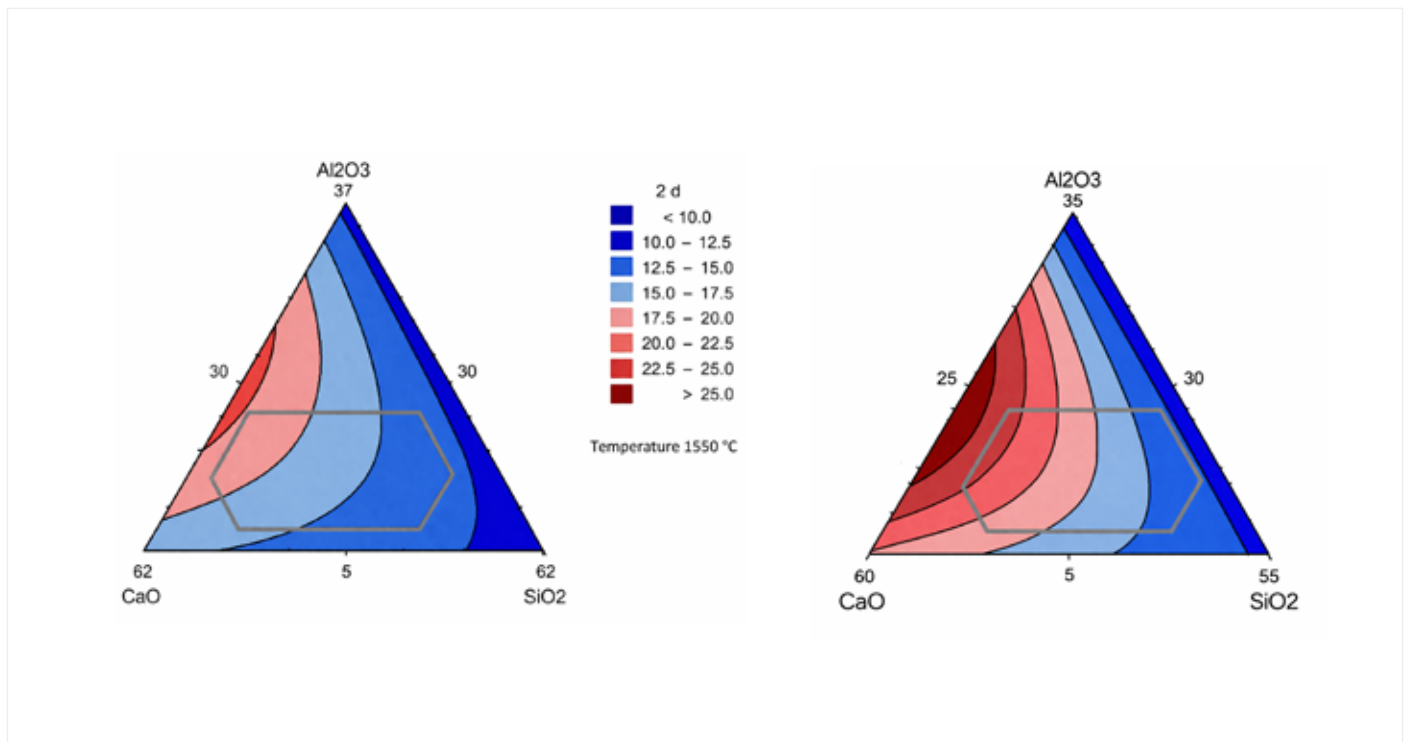


Figure 7: Impact of basicity and Al_2O_3 content at two MgO levels (left: 3 wt.%, right: 10 wt.%) on 2-day compressive strength of mortars according to DIN EN 196-1 at a melting temperature of 1,550°C for combinations of 50 wt.% laboratory slag and CEM I 42.5 R

The fact that the reactivity of EHMS varies as a function of its chemical composition analogously to granulated blast furnace slag is further confirmed by investigations targeting individual components. Figure 8 illustrates the well-known negative influence of significantly elevated TiO_2 contents at otherwise largely constant chemical composition. It should be noted, however, that within the DoE a superimposed, also negative, reduction of B_3 basicity, $(CaO + MgO)/SiO_2$, occurred simultaneously. (SC2-ST-6: 0.41 wt.% respectively 1.23; SC2-ST-16: 1.89 wt.% respectively 1.17; SC2-ST-9.3: 3.34 wt.% respectively 0.99; HS 1: 0.69 wt.% respectively 1.54).

Since future EHMS are expected to exhibit significantly higher V_2O_5 content compared to conventional granulated blast furnace slag due to raw material characteristics, its potential influence on reactivity was also investigated. As illustrated in Figure 9 by two examples, a negative influence is suggested. However, the superimposed effect of lower basicity must again be considered. (SC2-ST-6: 0.01 wt.% re-

spectively 1.23; SC2-ST-55: 3.46 wt.% respectively 0.98; HS 1: 0.01 wt.% respectively 1.54).

Despite very intensive water granulation at the FEhS-Institute, high glass contents could not be achieved for all slags. The reason was a high slag viscosity at the selected melting temperature combined with high basicity and pronounced crystallisation tendency. Nevertheless, as shown in Figure 10, a high strength contribution of such slags could be determined.

The formation of merwinite, $Ca_3Mg(SiO_4)_2$, is assumed to cause enrichment of Al_2O_3 in the glass phase and thus increased reactivity. These results once again demonstrate that a high glass content alone is not a sufficient prerequisite for producing a reactive and cement-technically usable material.

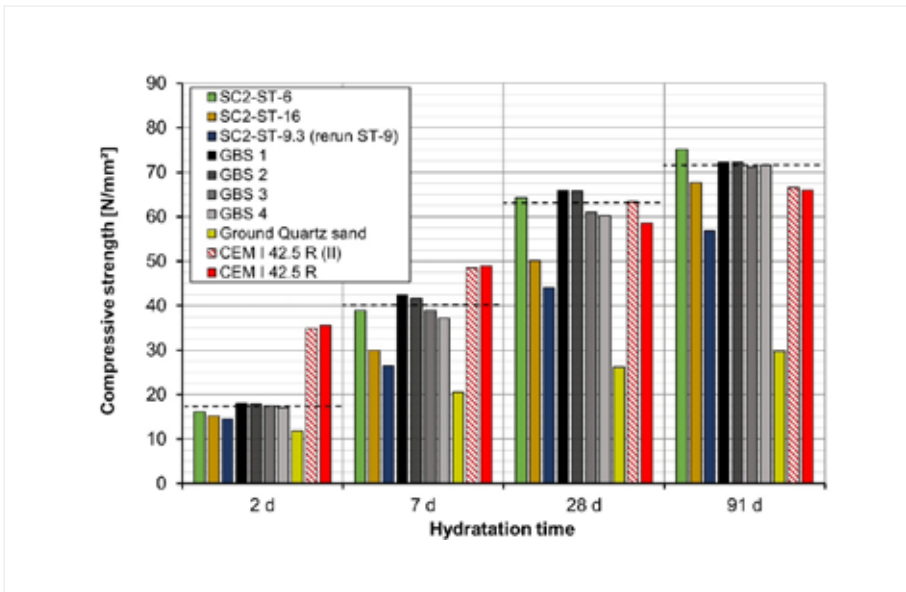


Figure 8: Influence of TiO_2 content on compressive strength of mortars according to DIN EN 196-1 for combinations of 50 wt.% laboratory slag and CEM I 42.5 R

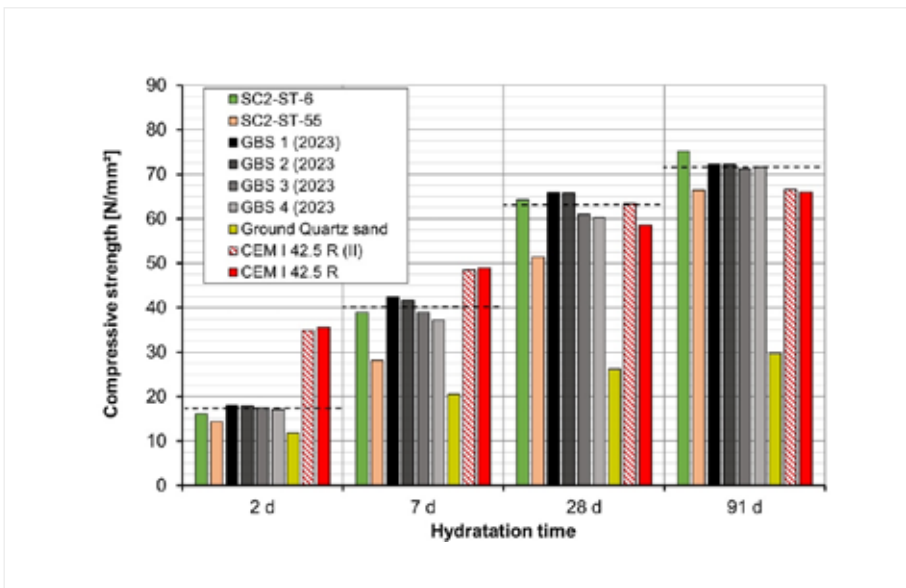


Figure 9: Influence of V_2O_5 content on compressive strength of mortars according to DIN EN 196-1 for combinations of 50 wt.% laboratory slag and CEM I 42.5 R

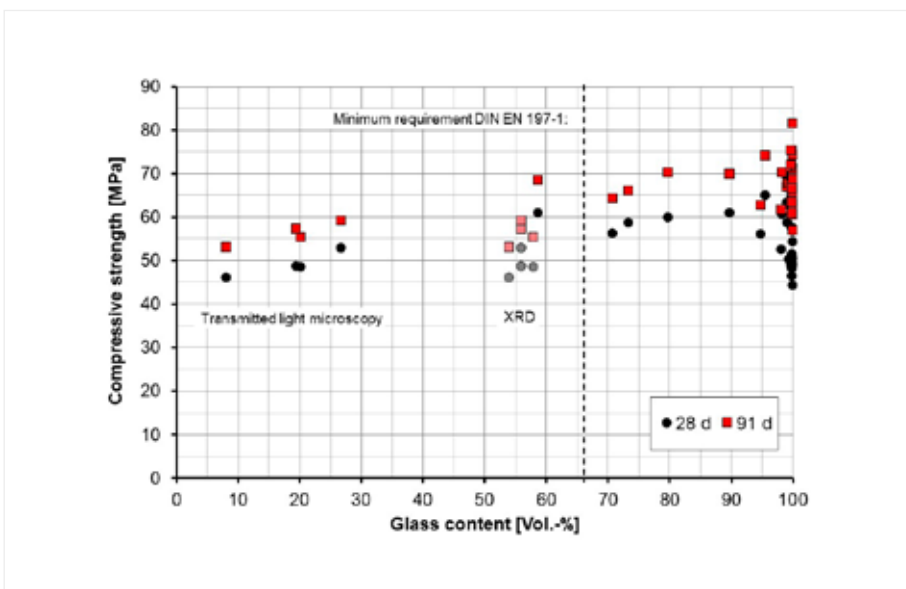


Figure 10: Influence of glass content on compressive strength of mortars according to DIN EN 196-1 for combinations of 50 wt.% laboratory slag and CEM I 42.5 R

Based on the experimental results, it is possible to estimate for future EHMS how targeted changes in chemical composition affect cement-technical performance. In particular, boundary conditions can be defined under which sufficiently low viscosity of the liquid slag can be achieved while at the same time ensuring a minimum reactivity of the granulated slag.

LARGE-SCALE TRIALS IN A SMELTER

Execution of the trials

Two large-scale experimental campaigns were carried out in July 2023 and July 2024 in an open submerged arc furnace (SAF). In total, approximately 66 tonnes of DRI and about 11.7 tonnes of additional input materials were processed.

The large-scale trials enabled numerous process-relevant observations that would only have been accessible to a limited extent at laboratory scale. These include, for example, the melting behaviour of the burden cone on the surface of the melt bath. Due to the material density and resulting pile height, corre-

sponding input quantities are required for its formation. The burden cone plays a crucial role in carburisation of the iron in the melt.

The interactions relevant for carburisation between slag, metal bath and burden cone are schematically illustrated in Figure 11. During the large-scale trials, a burden cone formed and was maintained throughout the entire test period by continuous addition of the input mixture. The burden cone remained mobile, and no segregation phenomena occurred.

This ensured a stable process, both from an electrical perspective, without arcing or instabilities, and from a process-metallurgical perspective, with production of processable hot metal of the desired carbon content and a metallurgically appropriate slag.

Based on the slag quantities generated in the individual sub-trials, sufficient amounts of mainly glassy material were produced by subsequent water granulation, see Figure 12. The different batches were then

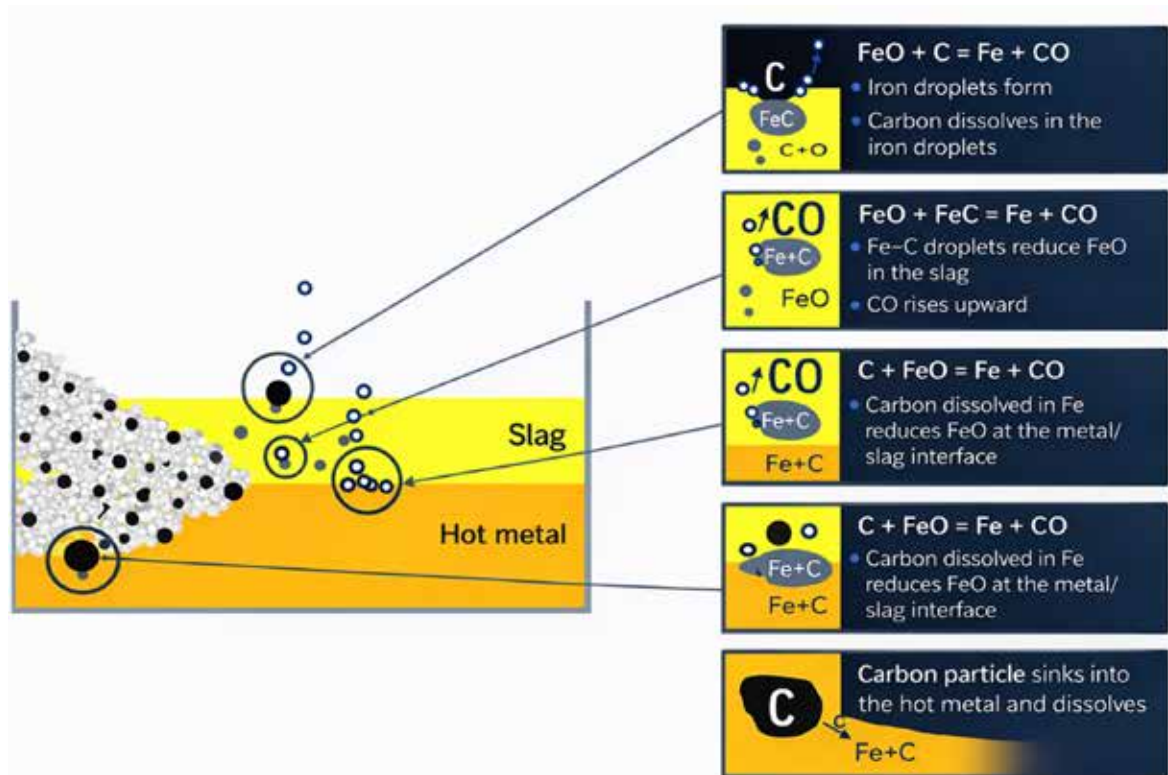


Figure 11: Interactions between DRI and the slag and metal phases



Figure 12: Water granulation of EHMS during the second large-scale campaign

comprehensively characterised chemically, mineralogically, physically and with respect to cement and concrete performance.

Electric hot metal slags from the large-scale trials and separate blast furnace slags

From the first large-scale campaign, two slag samples were available for further investigation; from the second campaign, six samples were available.

All samples were examined in detail with respect to:

- chemical composition; major, minor and trace elements
- mineralogical composition, in particular the glassy, potentially latent hydraulic fraction
- physical properties, true density, bulk density, particle size distribution, grindability
- environmental properties, leaching behaviour
- cement-technical performance

The results presented below focus on the second large-scale campaign, as it realistically reflected the boundary conditions of a future industrial plant. The first campaign resulted in slags that were less representative of future EHMS due to the materials used, for example scrap additions.

Within the SAVE CO₂ project, operational adjustments of slag composition were additionally investigated at tkSE blast furnace

No. 9. The background of these trials was the expectation of significantly lower basicities in future EHMS, which are generally associated with reduced reactivity. This was counteracted by targeted increase of Al₂O₃ content. Three of these industrially produced granulated blast furnace slags were made available for investigation. In addition, a corresponding laboratory granulated blast furnace slag was produced at the FEhS-Institute.

Chemical composition and glass content of EHMS from the second large-scale campaign

The chemical compositions and glass contents of the slag variants produced during the second large-scale campaign are summarised in Table 4.

Variant 1 was produced by remelting a conventional tkSE granulated blast furnace slag and served as a reference. In variants 1 to 4, compositions were adjusted through different combinations of granulated blast furnace slag, pig iron ingots, slag formers and other input materials, corresponding to varying DRI shares:

- Variant 1: 20%
- Variant 2: 50%
- Variant 3: 70%
- Variant 4: 30%

Variant 5 was primarily used for metallurgical investigations.

For comparison, both data from a granulated blast furnace slag from tkSE blast furnace No. 1 and results from FEhS monitoring of granulated blast furnace slags from member plants between 2008 and 2020 were used.

The granulated blast furnace slag from blast furnace No. 1 exhibited high reactivity and therefore represents a demanding reference. On long-term average, however, this slag shows a lower basicity $(CaO + MgO)/SiO_2$ of approximately 1.35 instead of 1.54, a lower F-value of 1.59 instead of 1.79, an MgO content of 5.8 wt.% instead of 6.6 wt.%, and a higher TiO_2 content of 1.14 wt.% instead of 0.69 wt.%. Consequently, its mean reactivity is lower.

The contents of major and minor constituents of the granulated electric hot metal slags largely corresponded to those of typical granulated blast furnace slags.

Table 4: Chemical composition and glass content of the EHMS produced in the second large-scale trial

FEhS-No.		Trial 0 P24-001002-01	Trial 1 P24-001002-02	Trial 2 P24-001002-03	Trial 3 P24-001002-04	Trial 4 P24-001002-05	Trial 5 P24-001002-06	GBFS BF1 P23-000131-01	GBFS Median 2008-2020
SiO ₂	M. %	35.6	36.7	34.7	33.1	35.7	35.6	32.7	36.9
Al ₂ O ₃		14.9	15.5	16.7	19.3	16.3	17.1	11.4	11.6
FeO		1.14	0.20	0.82	0.83	0.19	0.53	0.55	0.34
TiO ₂		0.70	0.76	0.71	1.07	0.98	1.13	0.69	0.75
MnO		0.16	0.08	0.03	0.06	0.06	0.07	0.22	0.34
CaO		39.6	39.2	40.4	39.4	39.3	38.3	43.8	41.0
MgO		5.86	5.96	5.16	4.65	5.85	5.75	6.60	7.32
Na ₂ O		0.19	0.33	0.20	0.30	0.41	0.45	0.22	0.28
K ₂ O		0.44	0.24	0.06	0.09	0.24	0.19	0.74	0.54
S _(total)		0.46	0.23	0.19	0.12	0.22	0.82	1.45	1.06
S ²⁻		0.43	0.21	0.17	0.13	0.21	0.75	1.24	0.99
SO ₃		0.20	0.14	0.12	0.12	0.11	0.11	0.20	0.10
P ₂ O ₅		0.02	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Cr ₂ O ₃		0.13	0.02	0.07	< 0.01	< 0.01	0.04	0.07	< 0.10
Cl ⁻		0.006	0.007	0.010	0.003	0.003	0.006	0.008	0.007
CO ₂		0.06	0.04	0.07	0.04	0.02	0.02	0.15	0.10
H ₂ O		0.03	0.18	< 0.01	0.04	< 0.01	< 0.01	0.04	0.09
C/S	1.11	1.07	1.17	1.19	1.10	1.08	1.34	1.12	
(C+M)/S	1.27	1.23	1.31	1.33	1.27	1.24	1.54	1.31	
F-value*	1.61	1.57	1.72	1.84	1.64	1.64	1.79	1.53	
Glass	vol. %	99.9	100.0	99.8	100.0	99.9	99.9	99.9	

$$*F\text{-value} = [(CaO + 0.5*MgO + 0.5*S^{2-} + Al_2O_3)/(SiO_2 + MnO)]$$

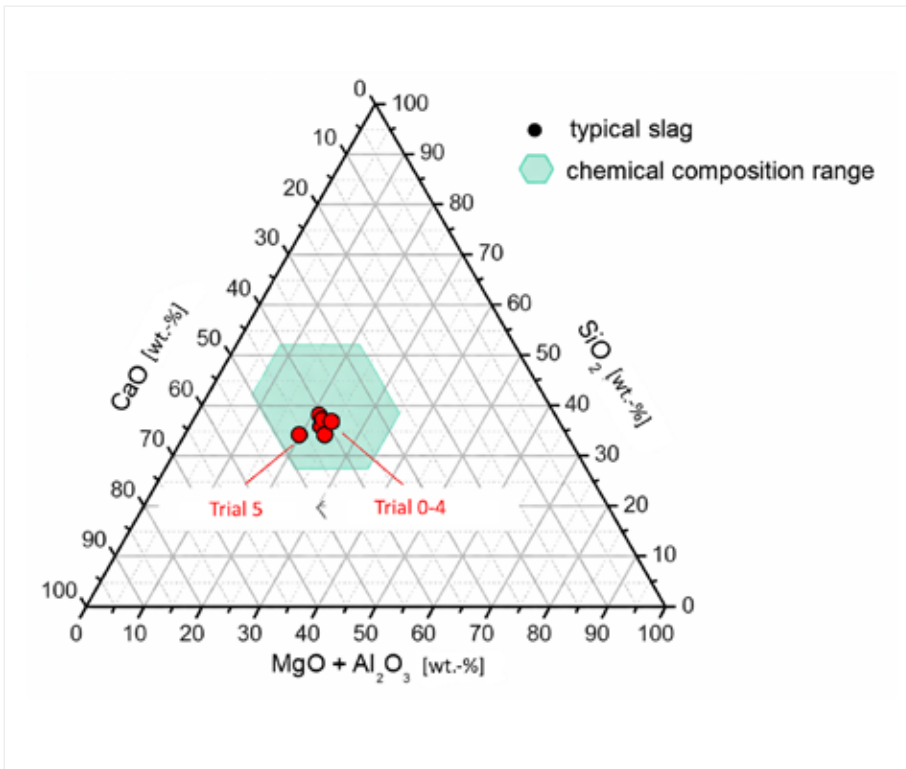


Figure 13: Classification of electric hot metal slags relative to blast furnace slags or granulated blast furnace slags registered under REACH [5]

Compared to the granulated blast furnace slag from tkSE blast furnace No. 1, the EHMS exhibited, at significantly lower CaO/SiO_2 and $(\text{CaO} + \text{MgO})/\text{SiO}_2$ basicities, higher Al_2O_3 contents and lower TiO_2 contents. In addition, the EHMS were lower in sulphur, and MnO contents were below the already low values of conventional granulated blast furnace slags.

While lower basicity generally suggests reduced reactivity in cementitious systems, elevated Al_2O_3 contents and lower TiO_2 and MnO contents are to be evaluated positively in this respect.

Figure 13 provides a graphical classification of the chemical compositions of the granulated EHMS compared to blast furnace slags or granulated blast furnace slags registered under REACH. It can be seen that the compositions of the EHMS, normalised to the four main components CaO , MgO , SiO_2 and Al_2O_3 , are located in the central region of typical blast furnace slags. The slag from trial 5 occupies a special position but also lies within the characteristic composition field of blast furnace slags.

The heavy metal contents of the EHMS were almost exclusively orders of magnitude below the limit values defined in ABuG [6], which are also used for the evaluation of new cement constituents. Only the slag from trial 0 slightly exceeded the limit value of 600 mg/kg for total chromium, with a value of 775 mg/kg. This is attributable to the quality of the pig iron ingots used. Chromium(VI) was not detected in any of the samples.

For all six granulated electric hot metal slags, the glass contents determined both by qXRD (quantitative X-ray diffraction) and by transmitted light microscopy on the ground fraction 40/63 μm were close to 100 vol.%. In comparison, the minimum requirement specified in DIN EN 197-x and DIN EN 15167-1 is only two-thirds.

Cementitious investigations of EHMS from the large-scale trials

The cement-technical investigations were carried out according to the same testing scheme described for the laboratory slags. The development of mortar compressive strength according to DIN EN 196-1 is shown in Figure 14.

For the 50/50 binder combinations, strength development largely corresponds to the median of the granulated blast furnace slag monitoring from 2008 to 2020. At 7 and 28 days, however, the strengths are significantly below those of the highly reactive reference slag HO 1, which can be attributed to the significantly lower basicity of the electric hot metal slags.

The 2-day strengths are predominantly determined by the clinker content; therefore, only minor differentiation is visible at this early age. Nevertheless, even after two days, the EHMS contribute actively to strength development compared to inert quartz filler.

After 91 days, the strengths of the cements containing EHMS and those containing the reference slag HO 1 largely converge and are generally slightly above the strength of pure Portland cement.

For the 75/25 combinations, the specific influence of the slag becomes more pronounced. The positive effect of elevated Al_2O_3 contents on early strength af-

ter two days is clearly visible. However, even after 91 days, the strength development remains below that of the cement containing the reference granulated blast furnace slag and only reaches the lower range of the monitoring values. In this case, the significantly lower basicity of the EHMS has a particularly negative effect.

Evaluation of cement-technical and environmental aspects

The workability properties of the cements consisting of granulated EHMS ground to conventional fineness combined with Portland cement, 50 wt.%, or clinker, 25 wt.%, with addition of sulphate carrier, showed no abnormalities.

The heat of hydration development corresponded to that of cements containing granulated blast furnace slags of comparable chemical composition and was generally at a low level.

Mortar investigations demonstrated the pronounced latent hydraulic potential of the granulated EHMS. In combinations with 50 wt.% Portland cement, the strengths after 91 days of hydration reached the level of Portland cement or of cement containing the highly reactive reference slag from tkSE blast furnace No. 1.

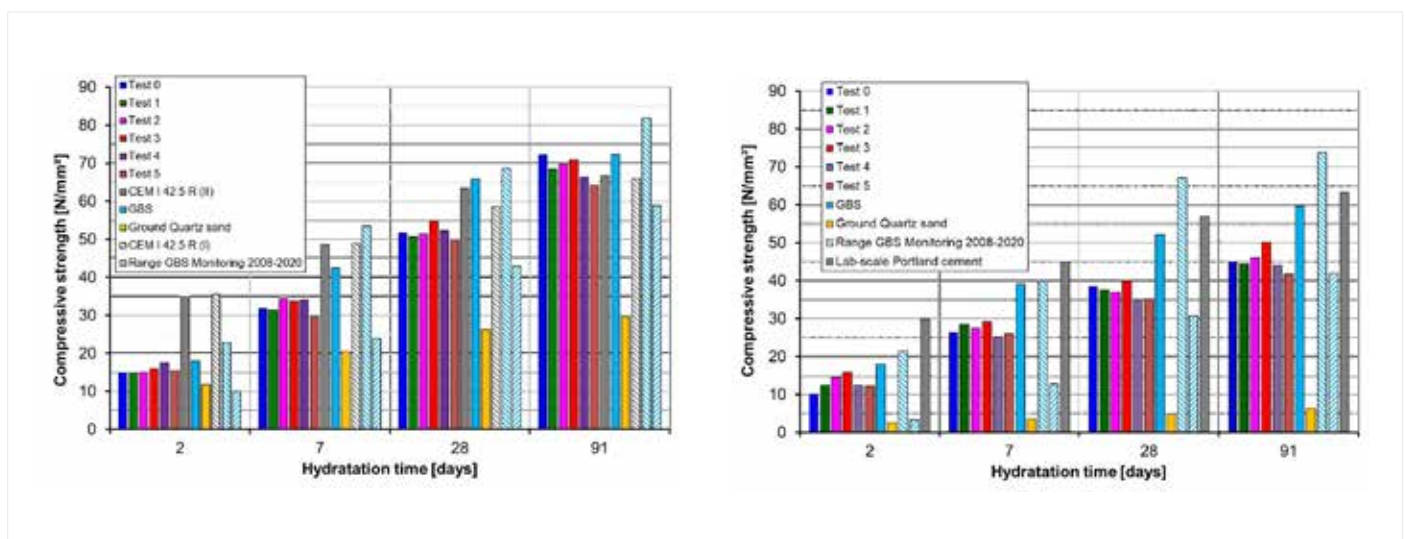


Figure 14: Development of compressive strength of mortars according to DIN EN 196-1 for combinations of 50 wt.% (left) and 75 wt.% (right) electric hot metal slag, granulated blast furnace slag and quartz filler with 50 wt.% and 25 wt.% Portland cement CEM I 42.5 R respectively

In combinations with 75 wt.% clinker, however, the strength level of the cements containing EHMS remained significantly lower even after 91 days. Overall, the influence of chemical composition on reactivity corresponds to the relationships long known for granulated blast furnace slag cements.

This also implies optimisation potential for future operational slags, which requires balancing increased raw material and energy input on the hot side of steel production against enhanced hydraulic reactivity.

Environmental aspects

The environmental compatibility of construction materials containing industrial by-products is evaluated in Germany based on solid material and eluate testing.

The chemical composition of the EHMS corresponded largely to that of the reference granulated blast furnace slag from tkSE blast furnace No. 1 as well as to typical granulated blast furnace slags.

The results were clearly within all solid material limit values defined in MVV TB and ABuG [6] for steelworks slags. Although these regulations formally apply to industrial aggregates in water-contact concrete according to DIN 1045-2, the defined limit values are regularly used in professional discussions of the German Institute for Building Technology (DIBt) for evaluation of new cement constituents and concrete additions.

Eluate testing of the granulated EHMS according to DIN EN 12457-4, water-to-solid ratio 10:1, showed that all measured concentrations were well below the defined limit values for steelworks slags.

Elution according to DIN 19529, water-to-solid ratio 2:1, as specified in the German Substitute Building Materials Ordinance (EBV) for road construction, also confirmed compliance with the limit values for material classes SWS 1, HS and HOS 1.

Concrete investigations

The objective of the concrete investigations was to evaluate the technical performance and potential application fields of the novel electric hot metal slags in comparison with established reference materials such as granulated blast furnace slag and hard coal fly ash.

For this purpose, compressive strength development and selected durability properties were determined in accordance with DIN EN 12350 and DIN EN 12390. Certain durability tests were carried out according to selected European national testing procedures for reasons of efficiency.

Three slags were selected for the concrete investigations:

- a slag from the first large-scale campaign, SAFS-1, whose chemical composition was specifically adjusted to resemble high-quality granulated blast furnace slag
- a slag from the second large-scale campaign, SAFS-2
- a modified granulated blast furnace slag from tkSE with low basicity and elevated Al_2O_3 content, GBFS-M

All three slags were comprehensively characterised with respect to physical, chemical and mineralogical properties.

The industrial reference materials used for comparison were conventional granulated blast furnace slag (GBFS) and hard coal fly ash.

Two Portland cements were used in the tests: CEM I 42.5 R and CEM I 52.5 R. All reference materials and cements were sourced from the operational business of Heidelberg Materials.

The novel slags and reference materials were tested in three commercially relevant cement formulations in both standard mortar and concrete:

- 66% CEM I 42.5 R + 22% SCM + 10% limestone filler + 2% anhydrite
- 51% CEM I 52.5 R + 38% SCM + 8% limestone filler + 3% anhydrite
- 28% CEM I 52.5 R + 65% SCM + 3% limestone filler + 4% anhydrite

The investigated slags were used as supplementary cementitious materials (SCM), replacing part of the base cement. The reference materials were hard coal fly ash in formulations 1 and 2 and granulated blast furnace slag in all three formulations. Limestone filler and anhydrite as the sulphate carrier originated from Heidelberg Materials plants.

Table 5: Standard requirement profile for granulated blast furnace slag according to EN 197-1 and EN 15167-1

Requirements according to EN 197-1 and EN 15167-1	Target value	GBFS	SAFS-1	SAFS-2	GBFS-M
Blaine (cm ² /g)	≥2,750	5,370	4,470	4,170	3,800
Glass content (wt.%)	≥66.6	94.6	93.8	99.8	99.9
(CaO+MgO)/SiO ₂	>1	1.27	1.52	1.27	1.16
LOI (wt.%)	≤3	0.55	+0.61	+0.59	+1.25
MgO+CaO+SiO ₂ (wt.%)	≥66.6	81.8	83.8	77.4	80.6
MgO (wt.%)	≤18	6.02	7.22	4.61	6.95
Sulphide S ²⁻ (wt.%)	≤2	1.18	0.47	0.15	1.06
Sulphate SO ₃ (wt.%)	≤2.5	2.81	0.94	0.30	2.57
Chloride Cl ⁻ (wt.%)	≤0.1	-	0.00	0.00	<0.01
Additional quality criteria:					
Basicity CaO/SiO ₂	>1	1.10	1.31	1.14	0.98
F-value*	-	1.51	1.83	1.75	1.45

$$*F\text{-value} = [(CaO + 0.5*MgO + 0.5*S2^- + Al_2O_3)/(SiO_2 + MnO)]$$

Testing was performed in standard mortar according to DIN EN 196-1 and in concrete according to DIN EN 12350 and DIN EN 12390.

Compressive strength

Concrete compressive strengths were determined up to an age of 182 days according to DIN EN 12390-3 and are summarised in Figure 15.

The results show that the novel slags achieved higher late strengths than the reference fly ash, while early strength development was approximately at the level of fly ash.

The slag SAFS-1, adjusted to resemble granulated blast furnace slag, exhibited comparable strength development to the reference granulated blast furnace slag at low cement substitution rates and even higher late strengths at higher substitution rates.

SAFS-2 and GBFS-M achieved strengths comparable to the reference slag and SAFS-1 at 22% cement substitution. However, with increasing substitution rates, a growing strength reduction relative to the reference slag was observed.

This effect is attributed to reduced calcium availability resulting from replacement of calcium-rich Port-

land cement. The slags were deliberately adjusted to lower calcium contents in order to reduce the CO₂ footprint of raw material input. The associated reduction in strength could not be fully compensated by the elevated Al₂O₃ content.

Additionally, the static modulus of elasticity according to DIN EN 12390-13 and porosity according to SN EN 262 were determined. For concretes containing EHMS, comparable elastic moduli in the range of 26,000 to 34,000 N/mm² were measured. Porosity ranged between 13 and 17 vol.%, corresponding to the reference concretes with granulated blast furnace slag.

Durability

The three cement formulations were investigated in mortar and concrete with respect to durability.

Based on freeze–thaw testing (CF method), the EHMS concretes can be classified as frost-resistant. Up to a cement substitution rate of 38%, the behaviour corresponded to that of reference concretes containing granulated blast furnace slag. At higher substitution rates, only SAFS-1 showed comparable performance.

Freeze–thaw de-icing salt resistance according to CEN/TS 12390-9 (CDF method) was confirmed up

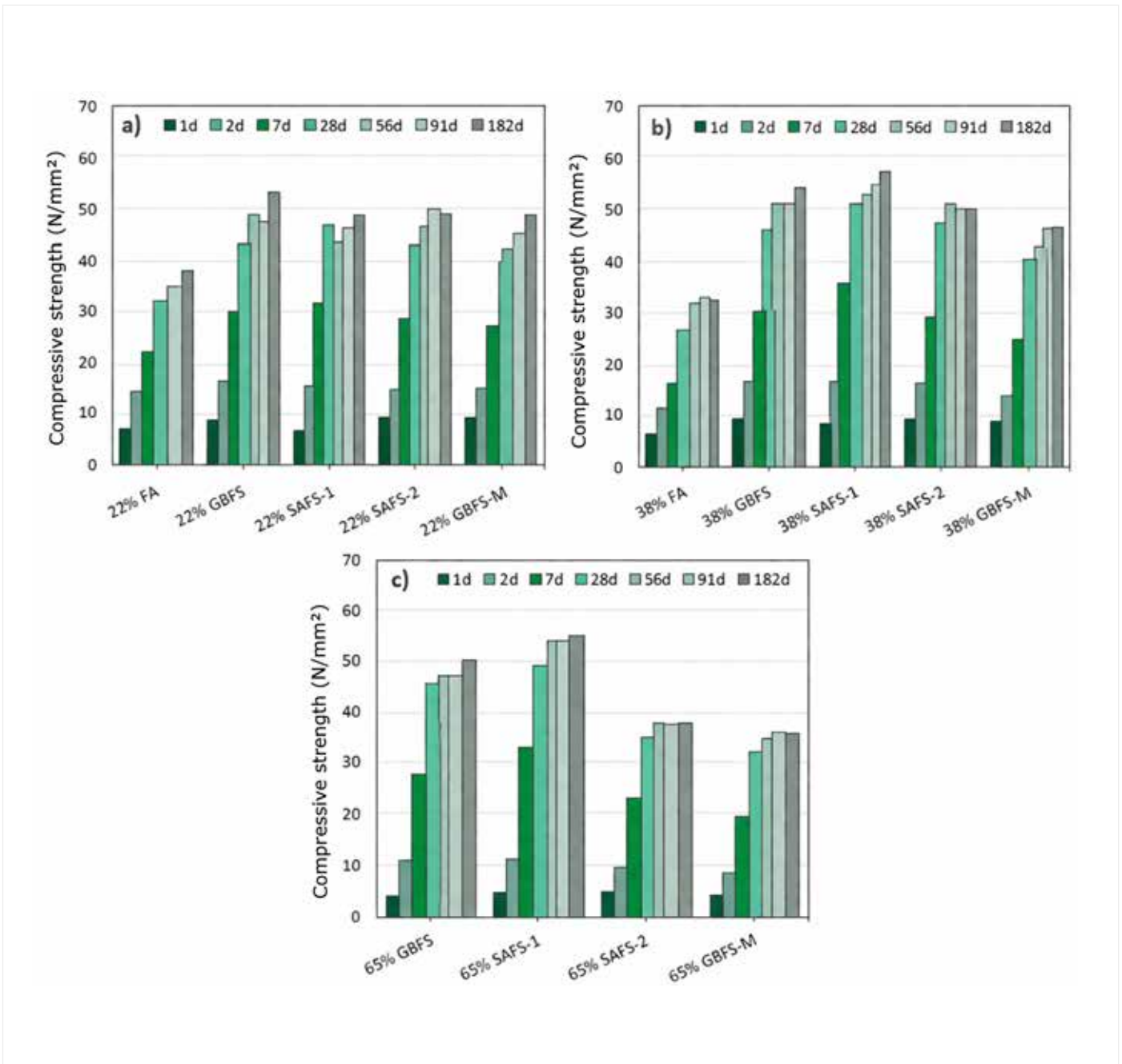


Figure 15: Compressive strength according to EN 12390-3

to a substitution rate of 38%. At 65% substitution, all specimens, including references, failed, which corresponds to the known behaviour of granulated blast furnace slag concretes.

Carbonation resistance, evaluated via CO₂ penetration depth, was higher for EHMS concretes than for fly ash references. SAFS-1 showed higher resistance than the reference granulated blast furnace slag across all substitution rates, whereas SAFS-2 and GBFS-M exhibited

increased susceptibility at 65% substitution. Overall, EHMS concrete formulations can be classified as carbonation-resistant.

Sulphate resistance according to the SVA method confirmed high sulphate resistance, particularly at substitution rates above 38%, with behaviour corresponding to that of granulated blast furnace slag binders.

Leaching behaviour

Leaching behaviour was evaluated using the dynamic surface leaching test on mortar prisms according to DIN EN 16637-2.

The focus was placed on critical elements such as chromium and vanadium.

The results show that the EHMS incorporated in mortar clearly complied with the applicable German limit values for chromium and vanadium, see Figure 16.

Determination of Cr(VI) was not necessary, since it occurs only in negligible concentrations in reduced slag. Instead, total chromium was analysed.

Overall, the electric hot metal slags produced can be classified as environmentally uncritical with regard to chromium and vanadium leaching.

ECONOMIC AND ECOLOGICAL EVALUATION

Within the SAVE CO2 project, life cycle assessments (LCA) were carried out in order to quantify the greenhouse gas emission reductions achievable through the processes developed.

In a simplified initial consideration, the additional efforts required for slag conditioning, necessary to enable the use of the novel slags in cement production, were evaluated in terms of greenhouse gas emissions.

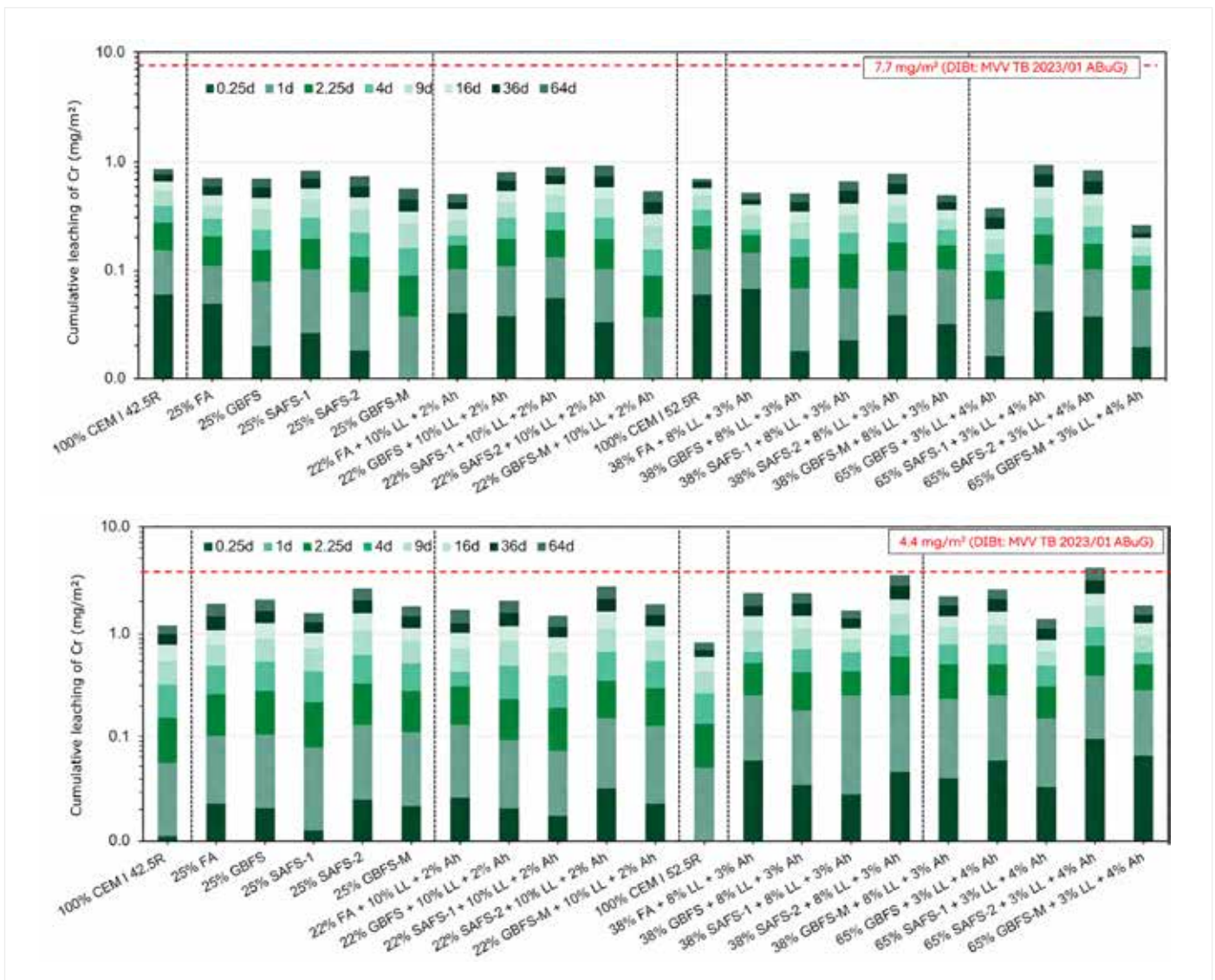


Figure 16: Cumulative leaching of Cr and V determined on standard mortar prisms according to EN 16637-2. In Germany, DIBt limit values according to MVV TB 2024, ABuG, apply for steelworks slags bound in concrete.

During the conditioning process, emissions of approximately 0.21 kg CO₂-equivalent per kilogram of slag are generated. This slag replaces ordinary Portland cement clinker (OPC clinker) at a ratio of 1:1. Since the carbon footprint of OPC clinker amounts to approximately 0.84 kg CO₂-equivalent per kilogram, a net saving of 0.63 kg CO₂-equivalent per kilogram of slag used is achieved.

Scenario description

Beyond this simplified calculation, three scenarios were analysed:

- Status quo scenario
- Steel production via the blast furnace route. The resulting conventional granulated blast furnace slags are used in the cement industry as clinker substitute.
- DR route without clinker substitution
Steel production via a hydrogen-based direct reduction route. The slags generated are not materially usable without further processing, so additional amounts of OPC clinker must be used in cement production.
- DR route with clinker substitution, SAVE CO₂
- The SAVE CO₂ processes developed within the project condition the novel slags from the DR route through targeted adjustment of chemical composition, enabling continued clinker substitution.

Since these scenarios involve changes in both steel and cement production, the system boundaries of the LCA were extended to include both industries. Although slag conditioning is technically carried out in the steel plant, the additional effort was allocated to cement production.

The following were evaluated:

- the carbon footprint of 1 kg of steel, blast furnace route versus DR route
- the carbon footprint of 1 kg of cement for scenarios 1 to 3
- the combined carbon footprint of 1 kg of steel and 0.34 kg of cement, comparison of scenario 1 versus scenario 3

Assumptions in the base case

In the base case, the following central assumptions were made:

Slags from the DR route chemically adjusted with lime to a basicity of approximately 0.7 were treat-

ed with a zero-burden approach when entering the SAVE CO₂ processes, meaning that no environmental burdens from steel production were allocated to them.

The entire energy supply of the system, including hydrogen production, was assumed to be based exclusively on renewable wind power from Germany.

LCA results

The carbon footprint of steel from the current blast furnace route amounts to 2.36 kg CO₂-equivalent per kilogram of steel, without credit for slags.

In contrast, steel produced via the hydrogen-based DR route shows a carbon footprint of 0.68 kg CO₂-equivalent per kilogram of steel, corresponding to an emission reduction of 71%.

For cement production, the scenario "DR route with clinker substitution" results in a carbon footprint of 0.55 kg CO₂-equivalent per kilogram of cement.

Without utilisation of the conditioned slags from the DR route, the carbon footprint of cement amounts to 0.84 kg CO₂-equivalent per kilogram.

Thus, the SAVE CO₂ approach reduces the product carbon footprint of cement by approximately 35%, from 0.84 to 0.55 kg CO₂-equivalent per kilogram.

The combined comparison of current production, scenario 1, and future production according to scenario 3, assuming a ratio of 1kg steel to 0.34 kg cement, shows a total greenhouse gas emission reduction potential of approximately 66%.

Sensitivity analyses

Sensitivity analyses demonstrate that the use of renewable energy can reduce greenhouse gas emissions of steel and cement production by up to 68% compared to the status quo.

Furthermore, it was shown that when applying economic allocation between steel and slag, a portion of the emission reductions can be attributed to steel production, allowing both industries to benefit from greenhouse gas savings.

Estimation of savings potential for Germany

In 2023, steel production in Germany amounted to approximately 31 million tonnes, of which about 70%, corresponding to 21.7 million tonnes, were produced via the blast furnace route.

Assuming that this amount is produced in the future via hydrogen-based direct reduction combined with SAVE CO₂ processes, approximately 21.7 million tonnes of steel and 7.3 million tonnes of slag-containing cement could be generated.

This potential cement quantity is significantly below the German cement production of approximately 35.5 million tonnes in 2020.

Under the stated assumptions, full transformation of the German steel sector would result in annual savings of approximately 18.7 million tonnes of CO₂-equivalent, provided sufficient renewable electricity and hydrogen are available.

SUMMARY AND OUTLOOK

Within the framework of the SAVE CO₂ project, investigations were carried out at laboratory and pilot scale to determine the suitability of novel electric hot metal slags from a smelter of the decarbonised primary steel production route for use as a latent hydraulic binder component in cement and concrete production.

The objective was to compensate for the expected loss of conventional blast furnace slags associated with the transformation of steel production and to continue reducing greenhouse gas emissions in the cement industry. It was taken into account that DRI typically contains an acidic gangue, which must be compensated by lime addition in the smelter in order to produce a sufficiently low-viscosity slag.

Laboratory investigations demonstrated that glass formation, and thus potential latent hydraulic reactivity, of the synthetically produced slags can be specifically controlled via chemical composition. Basicity and aluminium oxide content proved to be the decisive influencing parameters. Strongly merwinitic compositions with elevated basicity exhibited pronounced crystalline solidification. In contrast, moderate basicities combined with elevated Al₂O₃ contents, as well as low CaO/SiO₂ ratios, enabled high

glass contents, in line with established knowledge for blast furnace slags. The influence of MgO remained minor within the investigated system boundaries.

Minor constituents such as Na₂O, K₂O and V₂O₅, which may be introduced in increased amounts through DRI use, showed no relevant influence on glass formation. TiO₂ contents above approximately 1 wt.%, however, significantly reduced hydraulic reactivity.

Cement-technical investigations of the laboratory slags confirmed that their reactivity depends on chemical composition analogously to conventional granulated blast furnace slags. Although strength development varied considerably in some cases, an active strength contribution compared to inert filler was observed in all cases at early ages. The results demonstrate that a high glass content alone is not a sufficient prerequisite for high cement-technical performance but must always be evaluated in conjunction with the chemical composition of the glass phase.

The two large-scale campaigns conducted in the open submerged arc furnace confirmed the transferability of laboratory findings to semi-industrial scale. Stable operating conditions could be established under realistic process parameters, and sufficient quantities of largely fully glassy EHMS were produced by downstream water granulation. The chemical composition of the slags was within the range of typical blast furnace slags, characterised by lower basicities, higher Al₂O₃ contents and lower TiO₂, MnO and sulphur contents.

Cement-technical investigations of the granulated EHMS from the large-scale trials demonstrated a high latent hydraulic potential. In blends with 50 wt.% Portland cement, 91-day strengths reached the level of Portland cement or of cements containing highly reactive reference slags. At higher clinker substitution rates, the expected negative influence of lower basicity became apparent, particularly at early and intermediate hydration times. Overall, the observed relationships correspond to long-established principles for granulated blast furnace slag cements. Concrete investigations confirmed the fundamental suitability of the novel slags as supplementary cementitious materials. EHMS adjusted to higher calcium contents exhibited performance comparable to

conventional granulated blast furnace slag even at high substitution rates. Slags with lower C/S basicity and elevated Al_2O_3 content showed reduced hydraulic reactivity but performed comparably to granulated blast furnace slag at moderate substitution levels. Durability testing, freeze–thaw, freeze–thaw de-icing salt, carbonation and sulphate resistance demonstrated behaviour comparable to that of granulated blast furnace slag concretes. Leaching investigations confirmed compliance with all relevant limit values.

The economic and ecological evaluation by means of life cycle assessment showed that conditioning of EHMS and their use as clinker substitutes can lead to significant greenhouse gas emission reductions. Despite additional efforts for slag formers, a substantial reduction in the product carbon footprint of cement is achieved compared to a DR scenario without clinker substitution. In the combined assessment of steel and cement production, total emission reductions of approximately two-thirds compared to the current situation were demonstrated, provided renewable energy supply is ensured.

Overall, the results confirm that novel electric hot metal slags from the direct reduction route have high potential as substitutes for conventional granulated blast furnace slag, provided appropriate process control and targeted chemical adjustment are implemented. For industrial realisation, optimisation is required to balance minimal raw material and energy input on the hot side of steel production against sufficient hydraulic reactivity of the slags.

The next steps include classification and registration under REACH and the necessary standardisation work for the use of EHMS as a cement constituent, analogous to established granulated blast furnace slag, prior to commissioning of the large-scale industrial plant at thyssenkrupp in the coming years.

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GOOD THINGS COME TO THOSE WHO WAIT: LONG-TERM TESTS BY THE CEMENT LABORATORY (PART 1)

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(FEhS – Institut für Baustoff-Forschung e. V.)

INTRODUCTION

Throughout its long history, the FEhS-Institute has carried out numerous research projects dealing with the durability of concrete. The focus was particularly on concretes containing blast furnace cements. The results of this work were presented in the "Report of the Research Institute" as well as in journals such as "beton", "Cement International" and "ZKG International" and at scientific conferences. Since the durability of concrete cannot necessarily be reliably predicted from laboratory tests, but at the same time the duration of research projects is limited to 2-3 years, the FEhS-Institute's cement laboratory has in some cases determined the properties of mortars and concretes exposed to aggressive conditions long after the end of the project and thus self-financed this research. On the one hand, this allows possible damage to the concrete to be investigated, and, on the other hand, it verifies whether the assessments based on laboratory tests were accurate. This article presents the results of a

series of tests dedicated to resistance to water and seawater containing sulphate, which have been conducted at the FEhS-Institute for a very long time.

RESISTANCE TO SULPHATE ATTACK

The attack of sulphates on concrete has been the subject of decades of research. As early as 1915, 1922 and 1932, Passow, Gary and Grün, for example, studied the behaviour of blast furnace slag cements and Portland cements in seawater and saline waters [1-23]. It has long been known that cements with higher granulated blast furnace slag content have increased sulphate resistance, as they reduce the C_3A content coming from the clinker and have a very dense structure that hinders the access of sulphate ions, preventing the formation of damaging ettringite in the cement paste. According to DIN EN 197-1, blast furnace cements with at least 66 wt.% of granulated blast furnace slag are classified as "SR" (sulphate-resistant) cements. However, for around 20 years, the German Institute for

Building Technology (DIBt) has also issued corresponding building approvals for SR cements with a lower granulated blast furnace slag content. The experience gained is based predominantly on blast furnace slag produced in Europe. Today, this has an average Al_2O_3 content of around 11.5 wt.%. However, blast furnace slag produced outside Europe can also have contents of over 20 wt.% due to the raw materials used. In the literature, such elevated Al_2O_3 contents are seen as having a critical potential for secondary ettringite formation, which damages the structure, if the concrete is exposed to increased sulphate loading [4, 5, 6].



Slag is increasingly being imported into Europe, as local production is clearly unable to meet demand and, in addition, the switch in steel production from the primary blast furnace/LD converter route to a combination of gas-based direct reduction in conjunction with an electric melting process will lead to a further decline in European slag production [7]. This raises the question of whether, under otherwise constant conditions (slag content, fineness, clinker mineralogy), significantly higher Al_2O_3 contents inevitably lead to reduced sulphate resistance.

In August 2010, the FEhS-Institute's cement laboratory began measuring the expansion of mortar prisms measuring $10 \times 40 \times 160 \text{ mm}^3$. The test specimens are stored in a 4.4% Na_2SO_4 solution with 29,800 mg/l SO_4^{2-} , predominantly

at 20°C , and in two cases also at a storage temperature of 8°C . Test specimens stored in saturated $\text{Ca}(\text{OH})_2$ solution are used for comparison. Measurements are usually taken twice a year. The solutions are also renewed on this occasion. The test conditions correspond to the former procedure of the DIBt Expert Committee (SVA), which is based on the Wittekind procedure [8]. While the latter worked with a reference storage in water, a main storage in a 2% Na_2SO_4 solution (14,400 mg/l SO_4^{2-}) and a w/c ratio of 0.6 in order to achieve a relatively open structure and thus evaluate the chemical resistance of the cement, not its physical resistance, the SVA method uses a reference storage in $\text{Ca}(\text{OH})_2$ solution and a w/c ratio of 0.5. This was intended to take into account practical positive conditions, such as those found in concrete

in terms of structure compaction and activation of any pozzolanic components. A maximum elongation of 0.5 mm/m after 91 days of sulphate storage was taken as a guideline value.

The high sulphate concentration, which far exceeds normal real-life conditions and was introduced in order to shorten the test duration, has always been opposed by the argument that in "such tests, time cannot be replaced by higher concentrations" [8]. In order to avoid secondary gypsum formation caused by the test procedure, which can occur even at significantly lower concentrations (1,200 mg/l [4] or 4,000 mg/l [5] SO_4^{2-}) and which can lead to failure, particularly of SR Portland cements, the modified SVA test method used today by the DIBt specifies a significantly lower sul-

Table 1: Chemical composition and glass content of the granulated blast furnace slags in wt.%

	GBS 234 India	GBS 239 China	GBS 243 China	GBS 273 India	Ø FEhS
XRF:					
SiO ₂	33.6	31.7	30.9	33.9	36.9
Al ₂ O ₃	23.0	20.0	22.2	22.0	11.6
MnO	0.47	0.50	0.33	0.55	0.34
FeO	0.53	0.41	0.46	0.90	0.34
TiO ₂	0.93	0.55	0.60	1.27	0.75
CaO	29.9	30.7	36.8	31.5	41.0
MgO	9.81	14.4	7.14	9.15	7.32
Na ₂ O equivalent	0.69	1.23	0.62	0.71	0.65
IR spectroscopy:					
H ₂ O	0.39	0.48	0.44	0.18	0.09
CO ₂	0.32	0.25	0.27	0.17	0.10
Titration:					
Sulphide	0.63	0.72	0.91	0.55	0.99
Gravimetry:					
Sulphate	0.08	0.10	0.30	0.15	0.10
Basicity:					
C/S0.89	0.97	1.19	0.93	1.12	
(C+M)/S	1.18	1.42	1.42	1.20	1.31
F value	1.74	1.81	2.02	1.65	1.53
Microscopy:					
Glass content	99.9	98.7	99.0	99.7	99.9

Table 2: Frame conditions of the long-term tests

GBS 234 India		GBS 239 China		GBS 243 China		GBS 273 India	
GBS/CL	T	GBS/CL	T	GBS/CL	T	GBS/CL	T
40/60	20°C	40/60	20°C	40/60	20°C	40/60	20°C
50/50		50/50		50/50	8+20°C		
60/40		60/40		60/40	20°C		
75/25		75/25		75/25	8+20°C		

phate concentration of 3,000 mg/l. However, in return, the test duration had to be extended to five years. Despite various efforts, there is still no uniform European test procedure for assessing sulphate resistance [9]. For this reason, and in particular to ensure that practical technical parameters are taken into account in sulphate testing, the FEhS-Institute and ibac at RWTH Aachen University have further developed a test procedure and defined associated

acceptance criteria in a joint IGF research project. This procedure is based on the change in the relative flexural strength of concrete test specimens and not on the strain curve of mortars [10].

The long-term investigations into sulphate resistance were or are being carried out with cements with different granulated blast furnace slag/clinker ratios (GBS/CL) (Table 1, Table 2). The glass content of the granu-

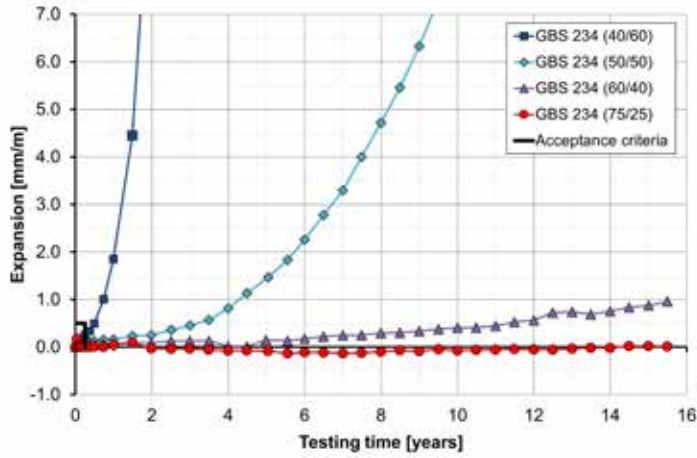


Figure 1: Expansions at 20°C for mortars with GBS 234

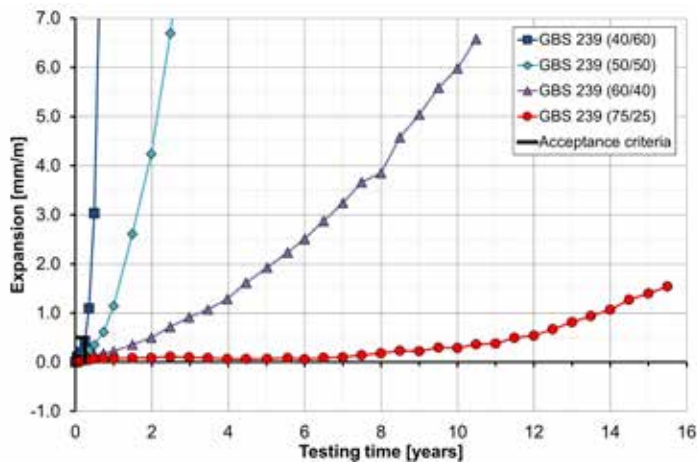


Figure 2: Expansions at 20°C for mortars with GBS 239

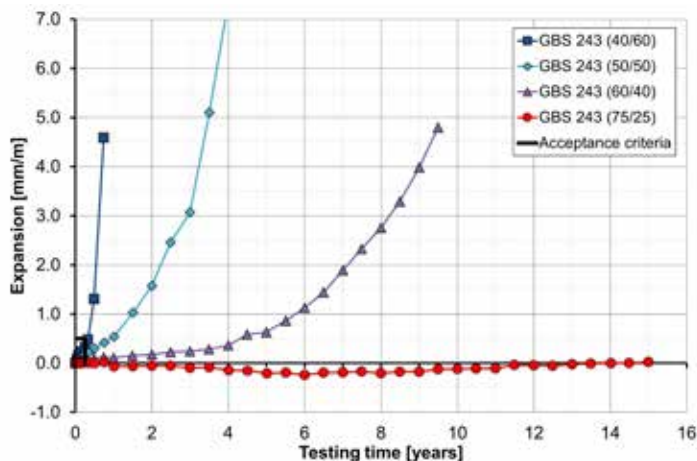


Figure 3: Expansions at 20°C for mortars with GBS 243

lated blast furnace slag was almost 100 wt.%. Due to their chemical composition (increased basicity, high Al_2O_3 content, low TiO_2 content), the two Chinese blast furnace slags can be described as highly reactive, whereas in the two Indian blast furnace slags, the low basicity and, in the case of blast furnace slag GBS 273, also the increased TiO_2 content, counteracted the positive effect of the high Al_2O_3 content. The blast furnace slag fineness was almost constant at around $4,200 \text{ cm}^2/\text{g}$ according to Blaine. The clinker had also been ground to this fineness. Its C_3A content was 8.7 wt.%. The SO_3 content of the cements was set uniformly at 4.5 wt.%.

Figures 1 to 4 show the expansions at 20°C for the mortars with the different slags at the four different GBS/clinker ratios. The expansions are currently measured twice a year, most recently in January 2026.

First of all, it is noteworthy that, with the exception of the mortar with GBS 239 at a GBS/CL ratio of only 40/60, all mortars met the acceptance criterion of 0.5 mm/m after 91 days of sulphate storage. However, the expansion of the mortars with all four granulated blast furnace slags increased very rapidly after exceeding 91 days at this low slag content. This highlights the problem of assessing sulphate resistance after only 91 days of sulphate storage.

As expected, sulphate resistance decreased with lower GBS content in the cement. For example, the mortar test specimens of GBS 234 with a GBS/CL ratio of 40/60 were “already” completely de-

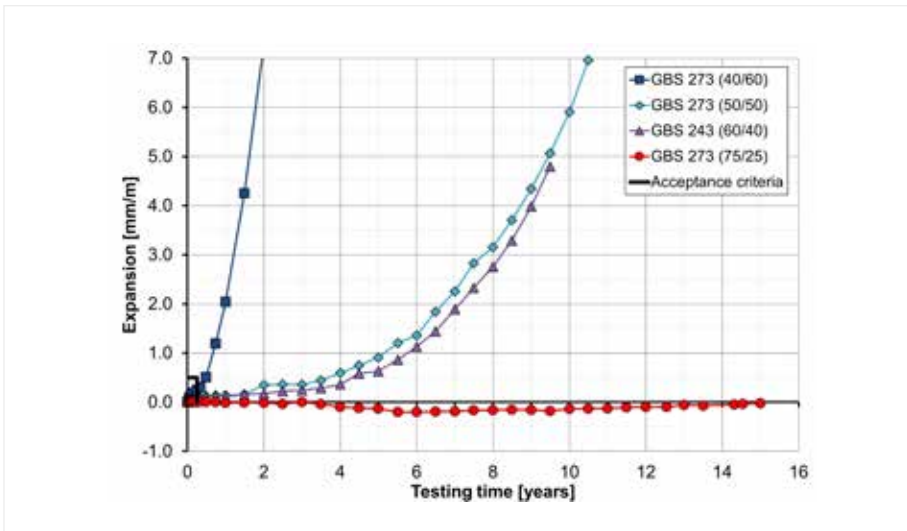


Figure 4: Expansions at 20°C for mortars with GBS 273

stroyed after 2.5 years (Figure 5), whereas the test specimens with a GBS/CL ratio of 50/50 were still intact after 3.0 years (Figure 6). It took another 10 years for significant cracks to become visible (Figure 7). While the mortars with a GBS/CL ratio of 60/40 show cracks for the first time after 15.5 years, their structure is still intact overall. The mortars with a GBS/CL ratio of 75/25, which corresponds to blast furnace cement CEM III/B, show no damage even after this long period of time (Figure 8).

It is noticeable that the mortars with GBS 239 and GBS 243, which

had higher basicities and had also shown higher strength development, exhibited significantly faster expansion than the mortars with GBS 234 and GBS 273, which had lower basicities.

The strain curve for mortar with GBS 273 at a GBS/CL ratio of 60/40 is striking from a measurement perspective. The curve is atypically very similar to the curve for mortar with a GBS/CL ratio of 50/50 (Figure 4). Although GBS 273 has the higher TiO_2 content (Table 1), meaning that theoretically a slower initial strength development and lower structural

compaction could be expected, the strengths determined in accordance with DIN EN 196-1 suggest that the higher Al_2O_3 content had a compensating effect. Almost 16 years after the test specimens were produced, it is of course no longer possible to determine whether a mistake was made during the production of the cement, e.g. whether the granulated blast furnace slag content was set too low.

Mortars with GBS/CL ratios of 50/50 and 75/25 were also stored at 8°C using GBS 243. Figure 11 shows the corresponding strain



Figure 5: Destroyed mortar test specimens with GBS 234 at a GBS/CL ratio of 40/60 after 915 days at 20°C



Figure 6: Intact mortar test specimens with GBS 234 at a GBS/CL ratio of 50/50 after 1,095 days at 20°C



Figure 7: Cracked mortar test specimens with GBS 234 at a GBS/CL ratio of 50/50 after 3,650 days at 20°C



Figure 8: Intact mortar test specimens with GBS 234 at a GBS/CL ratio of 75/25 after 4,380 days at 20°C



Figure 9: Intact mortar test specimens with GBS 243 at a GBS/CL ratio of 75/25 after 5,475 days at 8°C in Ca(OH)_2 solution



Figure 10: Intact mortar test specimens with GBS 243 at a GBS/CL ratio of 75/25 after 5,475 days at 8°C in Na_2SO_4 solution

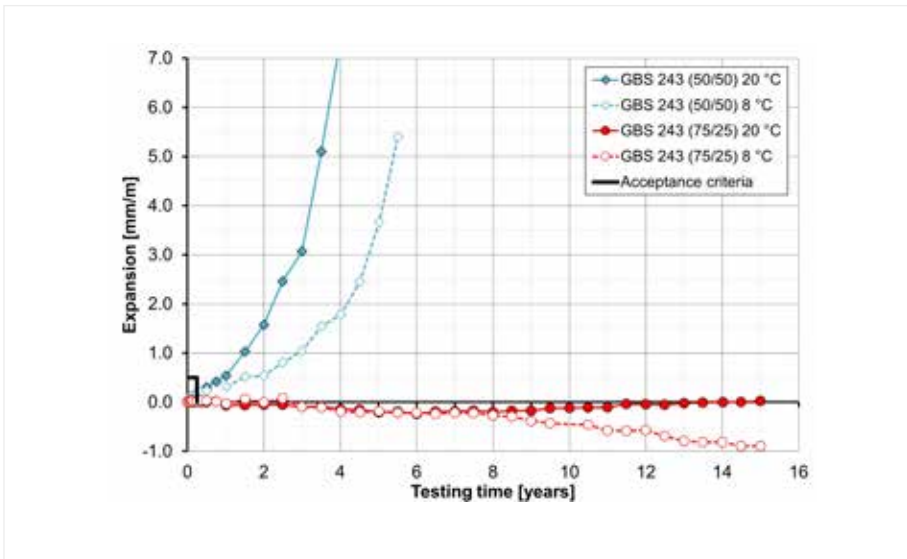


Figure 11: Expansions at 8°C and 20°C for mortars with GBS 243

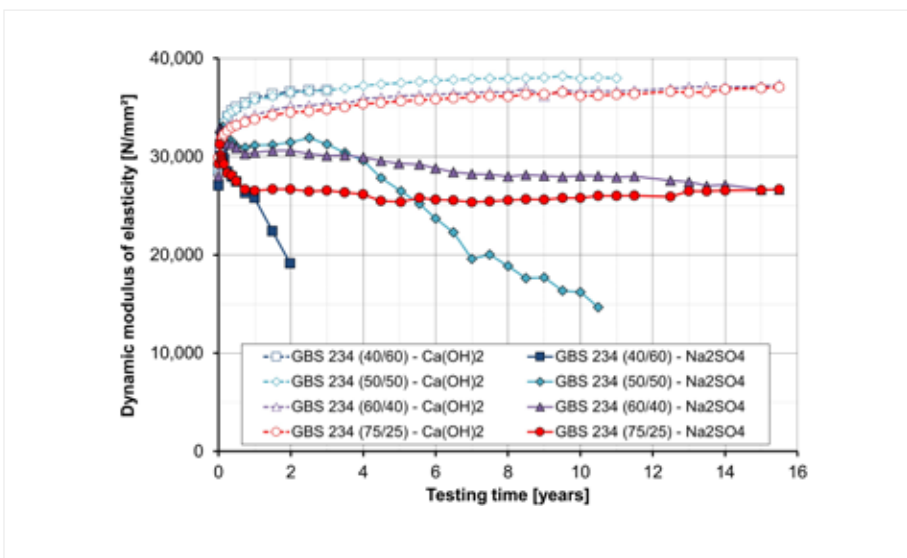


Figure 12: Dynamic modulus of elasticity at 20°C for mortars with GBS 234

curves. In the case of mortar with a GBS/CL ratio of 50/50, the expansion at 8°C occurred later than at 20°C. For the GBS/CL ratio of 75/25, the absolute expansion of the test specimens in the Ca(OH)_2 comparison solution has been higher than that of the test specimens in the test solution for years (Figure 9, Figure 10). Since the evaluation always considers a difference in expansion (main storage minus preliminary storage), the difference appears as shrinkage.

As early as the 1930s, it was suggested that the change in the dynamic modulus of elasticity be used as an indicator of sulphate-induced structural damage [8]. This is analogous to the acceptance criterion used today in the frost test for concrete according to the CIF test. In the long-term tests, the dynamic modulus of elasticity is also determined in addition to the expansion of the mortar prisms. For all four granulated blast furnace slags and all GBS/CL ratios, the mortars stored in Ca(OH)_2 solution showed a very similar development of the modulus of elasticity. This increased

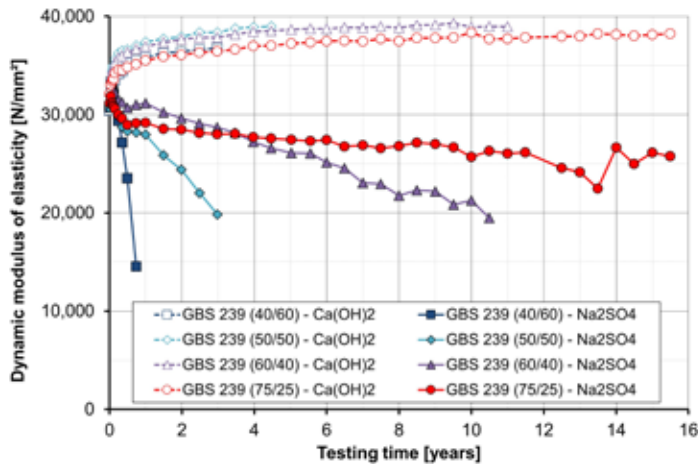


Figure 13: Dynamic modulus of elasticity at 20°C for mortars with GBS 239

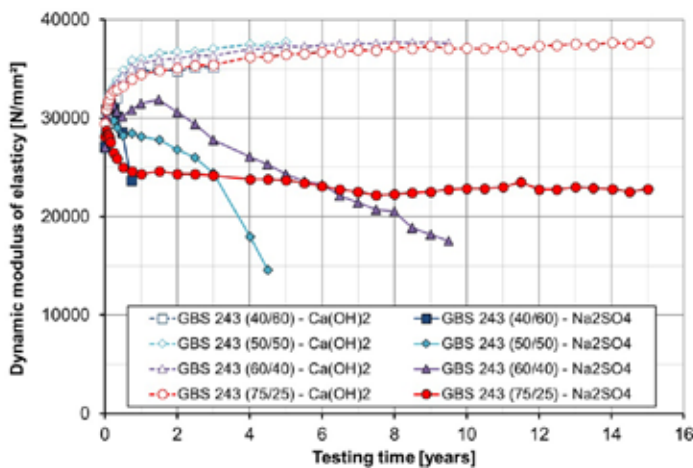


Figure 14: Dynamic modulus of elasticity at 20°C for mortars with GBS 243

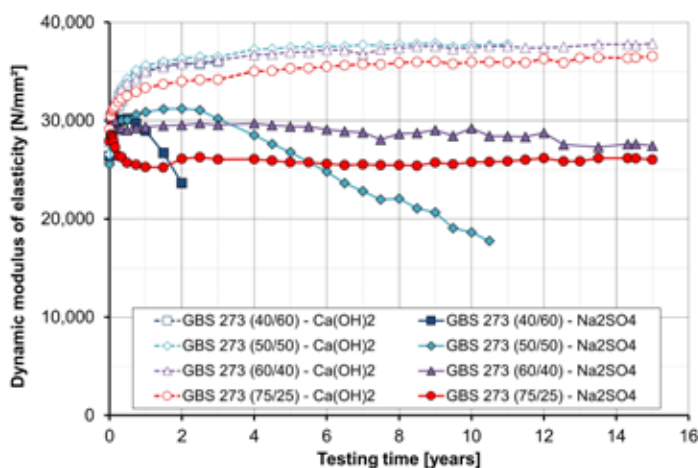


Figure 15: Dynamic modulus of elasticity at 20°C for mortars with GBS 273

in the first few months of storage and has since remained at a more or less constant level of around 37,000 N/mm². The development of the modulus of elasticity was different for the mortars stored in Na₂SO₄ solution.

Initially, the modulus of elasticity for all GBS/CL ratios rose briefly over a period of approximately 8 weeks. However, as the GBS content of the cement decreased, the modulus of elasticity then decreased significantly in correlation with the increasing elongation, which is consistent with the literature [8]. In mortars with a GBS/CL ratio of 75/25, a decrease in the modulus of elasticity can only be observed in the initial phase of storage (1 year), but this does not correlate with elongation. After this initial phase, the modulus of elasticity remains almost constant at around 2,000 N/mm² in most cases.

Figures 12 to 15 show the time curve of the modulus of elasticity at a storage temperature of 20°C. The curve for the mortar with GBS 239 and a GBS/CL ratio of 75/25 (Figure 13) is particularly striking. While the expansion became noticeable after approx. 10 years of storage and then increased steadily (Figure 2), the modulus of elasticity only showed a decline after approx. 12 years, which then disappears again despite further strain. Several effects are therefore obviously acting on the mortar structure, and there does not appear to be a simple relationship between sulphate attack, phase transformations, expansion and modulus of elasticity. Overall, the curves appear questionable. The curve profiles make it question-

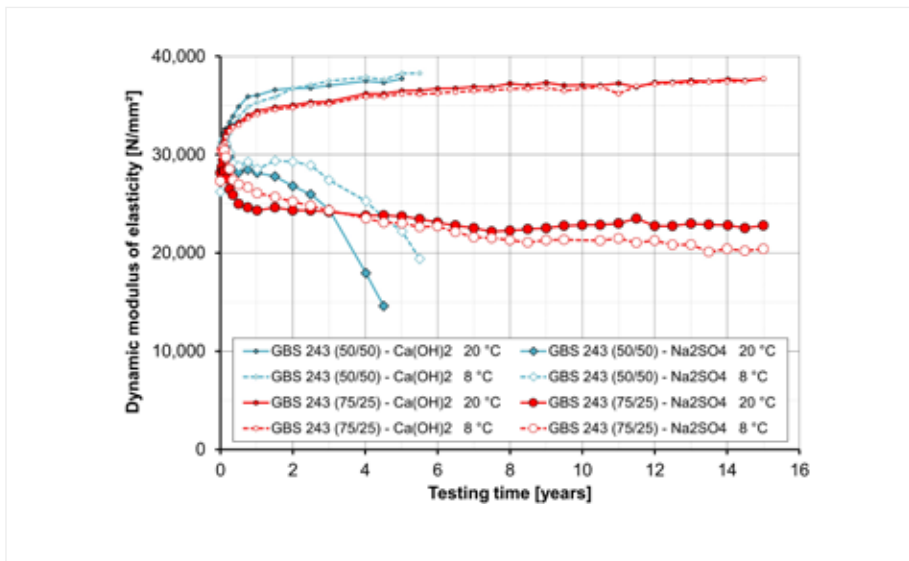


Figure 16: Dynamic modulus of elasticity at 8°C and 20°C for mortars with GBS 243

ble whether the decrease in dynamic modulus of elasticity can be used as a quantifiable evaluation criterion for the sulphate resistance of a cement.

Figure 16 shows the progression of the modulus of elasticity for mortar with GBS 243 at both 20°C and 8°C storage temperatures. While the progression is almost identical for both temperatures and both GBS/CL ratios when stored in Ca(OH)₂ solution, the behaviour differs when stored in Na₂SO₄ solution. While the lower temperature resulted in a significantly higher modulus of elasticity for mortar with a GBS/CL ratio of 50/50, only a slight temperature influence is noticeable for a GBS/CL ratio of 75/25.

In summary, it can be said that the measurement results collected over many years confirm, as expected, that blast furnace cements CEM III/B have high sulphate resistance and are therefore quite rightly classified as

“SR” cements in the standards. The Al₂O₃ content of the granulated blast furnace slag is irrelevant in this context. The situation is somewhat different for blast furnace cements CEM III/A with 50% by weight of granulated blast furnace slag. On the one hand, mortars containing these cements show significant expansion after a few years and, on the other hand, this expansion occurs much earlier in mortars containing the two types of granulated blast furnace slag with higher basicity. From the DIBt approval tests on blast furnace cements CEM III/A-SR with conventional European granulated blast furnace slags, it is known that higher slag fineness and higher clinker reactivity have a positive effect on sulphate resistance. It could therefore well be that the negative influence of higher Al₂O₃ contents can also be compensated for by appropriate measures. With regard to slag fineness, this had tended to be denied in the literature for blast furnace cements with less than 65 wt.% GBS [4],

but this can be refuted by the aforementioned approval tests.

Further long-term tests on sulphate resistance are being carried out in the cement laboratory using Slagstar® sulphate-resistant cement [11]. In 2004, it was not yet possible to perform reliable quantitative X-ray diffraction analysis according to Rietveld at the FEhS-Institute. Microscopic determination at that time revealed a GBS content of 77 wt.%, a sulphate carrier content of 18 wt.% and a clinker content of 4 wt.%.

The supersulphated cements produced from the first German approval in 1944 [12] until the 1970s are naturally considered to be cements with high sulphate resistance. GBS rich in Al₂O₃ (> 14-15 wt.%) was particularly suitable for these slag-dominated cements [13]. The investigations into Slagstar® are the result of a temporarily hoped-for renaissance of this type of cement, which was already standardised in Germany in 1953 in DIN 4210 and in Europe in 2010 in DIN EN 15743.

In addition to the investigations as described above for cements with different GBS/CL ratios (w/c = 0.5, reference storage in Ca(OH)₂ solution), the mortar flat prisms with Slagstar® were additionally produced and stored according to the Wittekind method (w/c = 0.6, reference storage in water). Storage in a 4.4% Na₂SO₄ solution was the same in both cases. The test series began in 2004 and have therefore been ongoing for 22 years. Measurements are taken every six months.

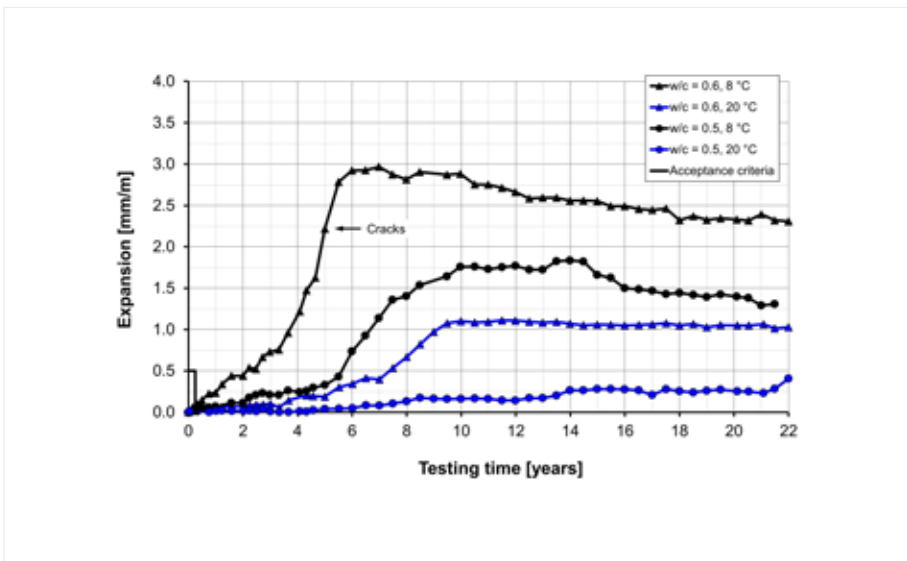


Figure 17: Expansion at 8°C and 20°C for mortars with Slagstar® (Wittekind method: w/c = 0.6 and reference storage in water, SVA method: w/c = 0.5 and reference storage in saturated Ca(OH)₂ solution)

Figure 17 shows the expansion curves for both test temperatures during storage according to the Wittekind and SVA methods.

Regardless of the conditions (w/c ratio, temperature, storage medium), the mortars containing sulphate-resistant cement easily met the requirement of a maximum expansion of 0.5 mm/m after 91 days. No significant expansion has been measured to date under standard storage conditions at 20°C according to the SVA

method. At 8°C, the expansion increased significantly between 6 and 10 years, but has since decreased again and did not reach a particularly high value, with a maximum of 1.8 mm/m. As expected, the expansions are higher at both temperatures with a higher w/c ratio and thus a more porous structure in the Wittekind method. At 20°C, a significant increase in elongation can be seen between 7 and 10 years, but this has remained constant since then. No damage is visible on the flat

prisms. At 8°C, there was a significant increase in elongation between 2 and 7 years. Since then, the elongation has been steadily decreasing again. The first cracks appeared after a storage period of 5 years. However, the mortar structure has remained intact to date (Figure 18). When stored according to the SVA method, no change in the mortar prisms has been observed to date (Figure 19).

X-ray diffraction analyses could show whether the cause of the increased expansion in individual cases at 8°C storage is due to thaumasite formation, whether the high sulphate concentration led to secondary gypsum formation over a long period of time, or whether secondary ettringite was actually formed. So far, this analysis has not been carried out in order to continue measurements on three intact test specimens.

The dynamic modulus of elasticity was also determined for the mortar test specimens with Slagstar® (Figures 20 and 21). With regard to the initially significant and then



Figure 18: Mortar test specimen with Slagstar® (w/c = 0.6) after 20 years of storage at 8°C

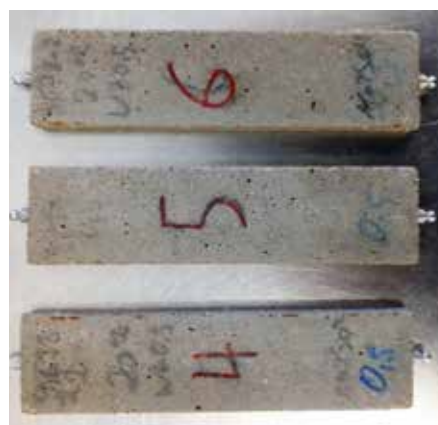


Figure 19: Mortar test specimen with Slagstar® (w/c = 0.5) after 20 years of storage at 20°C

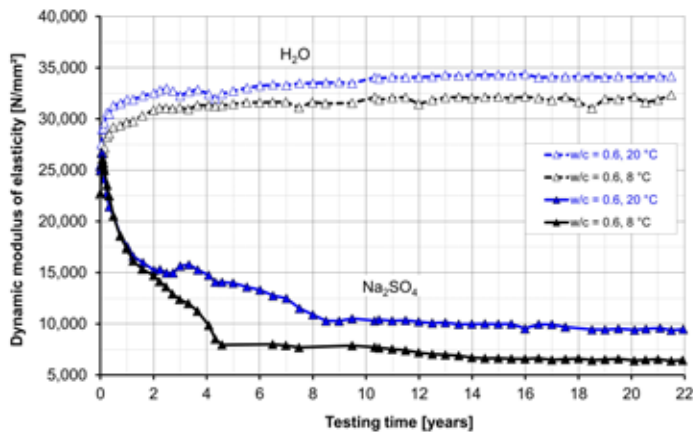


Figure 20: Dynamic modulus of elasticity at 8°C and 20°C for mortars with Slagstar® (Wittek method: w/c = 0.6)

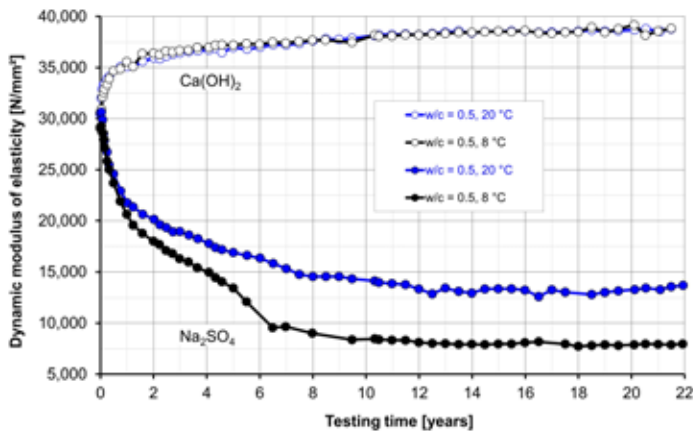


Figure 21: Dynamic modulus of elasticity at 8°C and 20°C for mortars with Slagstar® (SVA method: w/c = 0.5)

only slight increase in the modulus of elasticity for the reference specimens stored in water and Ca(OH)_2 solution, there are hardly any differences in terms of storage temperatures. The curves correspond to those described for blast furnace cements (Figures 12 to 15). However, the absolute modulus of elasticity values are slightly lower. In the test specimens stored in Na_2SO_4 solution, a significant drop in the modulus of elasticity to very low values can be observed, despite the fact that

hardly any expansion was measurable at the beginning of storage. The data collected on the supersulphated cement also show how problematic it is to evaluate sulphate resistance on the basis of the dynamic modulus of elasticity.

The results once again demonstrate the well-known high sulphate resistance of supersulphated cement, using Slagstar® as an example. Even though this cement has not experienced a renaissance for various reasons, there is still a

demand for it, especially when it comes to repairing structures that were once built with sulphate-resistant cement concrete. These include hydraulic structures, but also buildings such as the District Savings Bank Saarbrücken shown in Figure 22.

RESISTANCE AGAINST SEA-WATER ATTACK

In 2016, the FEhS-Institute was asked to provide concrete test specimens for the DFG research project "INTERCOAST" conducted



Figure 22: Saarbrücken District Savings Bank, built with supersulphated cement "Halit" from the former "Halberger Hütte"

by the Universities of Bremen and Waikato (New Zealand). The aim of the project was to investigate artificial coastal protection structures made of concrete, which is the most important building material for this purpose (around 70%). The motivation for the work was the expected rise in sea levels due to climate change and the consequent need for significant additional coastal protection meas-

ures worldwide. The results of the project were reported, for example, in [14-16].

In two campaigns, A and B, concrete cubes measuring 150 x 150 x 150 mm³ were produced at the FEhS-Institute in 2016 and 2017. These were stored in seawater at various locations (Jade-Weser Port Wilhelmshaven, Helgoland, Motiti Island, Tauranga Harbour) by staff

from the University of Bremen. The concretes varied in terms of the cements and aggregates used and met the requirements for exposure class XF 2 (Table 3). Iron silicate is crystalline copper slag. MagnaDense® is an iron ore (magnetite) and EAF is crystalline electric furnace slag. These aggregates were chosen to increase the bulk density of the concrete and thus its resistance to wave action.

After completing the work on plant growth, the FEhS-Institute took over the monitoring of the concrete test specimens at Jade-Weser Port in 2019 (Figure 23). The test specimens have been stored in three steel cages under water in the harbour basin since April 2017 (Figure 24). Since the cages are attached to a floating pontoon, the test specimens cannot run aground regardless of the tidal range. This means that even in very cold winters, there is no risk of frost damage. The test specimens are inspected every 1-2 years. To this end, the algae, mussels and barnacles that usually grow heavily on the test specimens are removed (Figure 25). Afterwards, the specimen mass and the dynamic modulus of elasticity are determined using ultrasonic transmitting time measurement.

Table 3: Concrete mixtures for structures exposed to seawater

No.	Cement type	Cement	Water	w/c	Aggregate					
		kg/m ³		-	Type	kg/m ³	Type	kg/m ³	Type	kg/m ³
M 1	CEM I 42.5 R	320	160	0.5	Sand 0-2 mm	667	Gravel 2-8 mm	95	MagnaDense® 20s	2,122
M 2	CEM III/A 42.5 N					664		95		2,112
M 3						662		95		2,107
M 4	CEM III/B 42.5 N-LH/SR/NA				Iron silicate 0-5 mm	1,361	Iron silicate 5-22 mm	1,358	-	-
M 5					Sand 0-2 mm	284	EAF 0-2 mm	2,193	-	-

The results are reported as relative values based on the initial measurement in 2019.

The temporal progression of the relative dynamic modulus of elasticity is shown in Figure 26 as a function of cement type. All three concretes were produced using MagnaDense 20s (MD 20s) as aggregate. The seawater temperature in the harbour basin

visual inspection. This was also the case for the concrete with Portland cement during the first 3 years of storage. However, the relative dynamic modulus of elasticity decreased slightly during this period. At the same time, initial spalling was observed, particularly at the corners of the concrete cubes, which cannot be attributed to storage damage (Figure 27).



Figure 23: Tugboat harbour of the Jade-Weser Port Wilhelmshaven



Figure 24: Storage of the concrete cubes in stainless steel cages in the water of the harbour basin



Figure 25: Flora and fauna on and around the test specimens in 2024; left: algae, mussels and barnacles; right: starfish and crabs

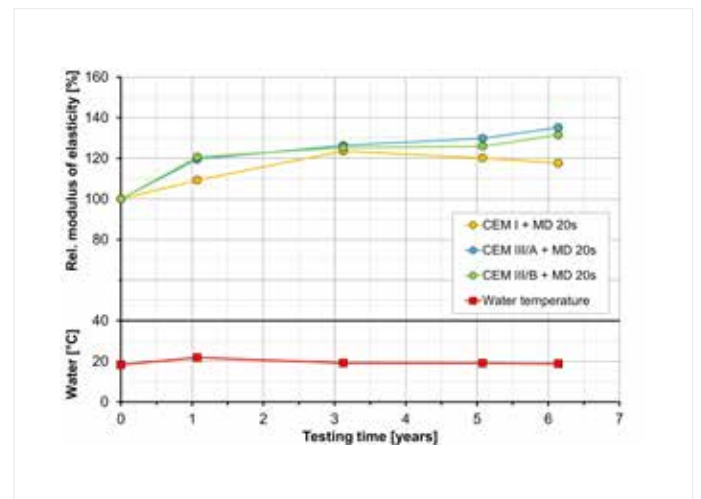


Figure 26: Relative dynamic modulus of elasticity of concretes with different cements and MagnaDense® as aggregate

on the respective test days is also shown. The relative dynamic modulus of elasticity of the concretes with the two blast furnace cements CEM III/A and CEM III/B rose continuously over the last 6 years. No spalling or cracks were found on the cubes during

Figure 28 shows the temporal progression of the relative dynamic modulus of elasticity of the concretes with the blast furnace cement CEM III/B and various aggregates. This figure also shows the seawater temperature in the harbour basin as determined



Figure 27: Corner spalling on concrete with Portland cement and MagnaDense® 20s

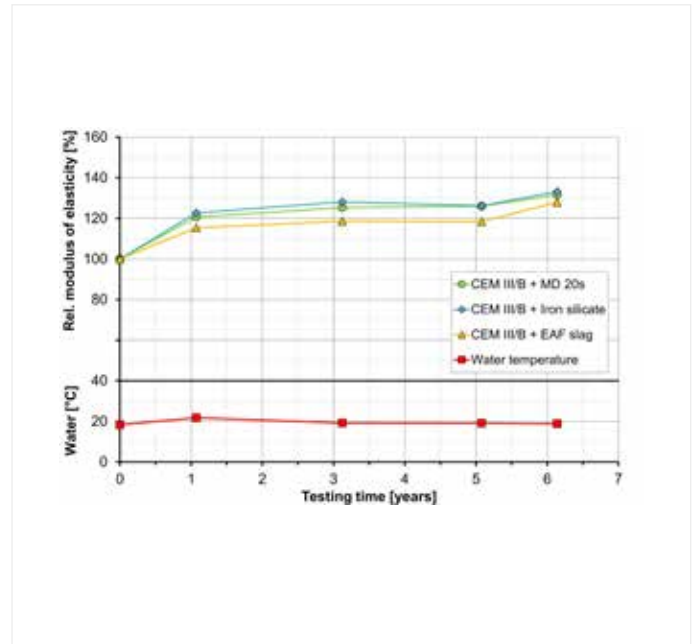


Figure 28: Relative dynamic modulus of elasticity of concrete with blast furnace cement CEM III/B and various industrial aggregates



Figure 29: Intact concrete test specimen with blast furnace cement CEM III/B and EAF slag as an industrial aggregate

during the tests. Regardless of the aggregate used, a continuous increase in the relative dynamic modulus of elasticity was observed in all concretes with CEM III/B. All test specimens showed only typical traces of fouling by mussels and barnacles. No visible structural damage, spalling or cracks were found even after 8 years of exposure, as shown in Figure 29 for the

test specimens of concrete with CEM III/B and EAF slag as an industrial aggregate.

It has been known for decades that concrete containing blast furnace cement is highly resistant to seawater attack. This has been confirmed in many outdoor exposure tests, some of which lasted for decades [17-22]. The results obtained during the 8 years of outdoor exposure to date also confirm this experience. However, the choice of cement type alone is not decisive for the high seawater resistance of concrete. Rather, the concrete mix (cement content, w/c ratio), concrete processing (compaction) and the general conditions (e.g. time of first contact with seawater) are also of central importance. Therefore, as early as 1959, after inspecting numerous seawater structures, it was determined that "it is not the type of cement, but the quality of the concrete that determines its resistance in seawater" [17]. The type of cement is particularly important when the cement content in the concrete is very low [20].

The results show that industrial aggregates, such as EAF slag or copper slag, are suitable for concrete exposed to seawater. The quantity and diversity of the vegetation and fauna show no negative effects on the environment, thus confirming the statements made in the "INTERCOAST" project [14, 15].

ADDITIONAL LONG-TERM TESTS

In addition to testing the resistance of mortar and concrete to attack by water or seawater containing sulphate, the cement laboratory is also conducting other long-term tests. The results of these tests will be presented in detail in one of the next "Reports".

The first project involves tests on 40 x 40 x 160 mm³ mortar prisms, which were produced as part of the IGF research project 13332 pursued jointly with the VDZ [23]. The cements contained varying amounts of granulated blast furnace slag, limestone and clinker, and the project was related to the introduction of the then new Portland composite cements CEM II/B-M (S-LL). In 2003 (!), the mortars were stored in water with lime-dissolving carbonic acid (100 mg CO₂/l) and in ammonium chloride solution (100 mg NH₄⁺/l). Figures 30 to 33 show the test specimens with a Portland limestone cement containing 35 wt.% limestone and a Portland blast furnace cement containing 35 wt.% GBS after 21 years of storage in water with lime-dissolving carbonic acid. For formulation B2, a w/c ratio of 0.45 and a cement content of 320 kg/m³ were set. For formulation B3, a w/c ratio of 0.70 and

a cement content of 300 kg/m³ were set. The images demonstrate the increased resistance of mortars with Portland blast furnace cement to lime-dissolving carbonic acid, which has been known for a long time [24].

The second project involves testing the removal of concrete containing various industrial aggregates. These aggregates were produced as part of the IGF research project 21567 [25]. In particular, the project is investigating whether the concrete's dimensional stability is guaranteed and whether the results determined under real conditions since 2021 correlate with those of the rapid test procedure further developed as part of the project. Figure 34 shows an example of a concrete beam measuring 100 x 100 x 500 mm³ that was produced using the electric furnace slag EOS-2 and shows no damage due to expansion or cracking after almost 4 years (1,392 days) of outdoor storage under a roof.

OUTLOOK

The results presented from the long-term durability tests on mortars and concretes with cement contain-



Figure 30: Mortar test specimen with Portland limestone cement after 21 years of storage in water with lime-dissolving carbonic acid (w/c = 0.45, c = 320 kg/m³)



Figure 31: Mortar test specimen with Portland limestone cement after 21 years of storage in water with lime-dissolving carbonic acid (w/c = 0.70, c = 300 kg/m³)



Figure 32: Mortar test specimen with Portland cement after 21 years of storage in water with lime-dissolving carbonic acid ($w/c = 0.45$, $c = 320 \text{ kg/m}^3$)



Figure 33: Mortar test specimen with Portland cement after 21 years of storage in water with lime-dissolving carbonic acid ($w/c = 0.70$, $c = 300 \text{ kg/m}^3$)

ing granulated blast furnace slag once again confirm the positive effect of GBS on the development of high physical and chemical resistance of the cement stone structure against various chemical attacks. It is planned to continue the measurements for as long as possible. Structure and phase investigations

should provide information on the changes that have occurred.

In the future, it will be necessary to show whether the positive effect of GBS-rich cements can also be achieved by the new slags expected in the course of the steel production transformation process. This can be expected if these slags can be converted into a largely glassy material analogous to blast furnace slag and react latently hydraulically, but this still needs to be verified. The first project of this kind, which is dedicated to the property of sulphate resistance, was already started in 2025 at the FEhS-Institute [26]. <<<



Figure 34: Intact concrete test specimen with electric furnace slag EOS-2 as an industrial aggregate after 1,392 days of outdoor storage under a roof

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PRODUCTION AND USE OF FERROUS SLAG IN 2024

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Ferrous slag (blast furnace slag and steel furnace slag) has been established on the market as a construction material and fertiliser for well over 100 years and is an example of a circular economy that works successfully in practice.

GERMANY

The data on production and use in Germany in 2024 are given in Tables 1 (blast furnace slag, BFS) and 2 (steel furnace slag, SFS). For comparison purposes, the data for the previous year is also provided in each case.

After steel production in Germany reached 35.4 million tonnes in 2023, this figure rose slightly again in 2024 to 37.2 million tonnes, although production of over 40 million tonnes was last achieved in 2021 [1]. Accordingly, the production of slag products also remains at a low level: In 2024, a total of 11.8 million tonnes of ferrous slag

Production	2024	2023
Granulated BFS	7.01	6.92
Air-cooled BFS	0.08	0.08
Sum	7.09	7.00
From interim storage	0.82	0.77
Total	7.91	7.77

Use	2024	2023
ABS for aggregates	0.15	0.18
ABS for aggregate mixtures	0.23	0.31
GBS for cement production	7.14	7.13
GBS for other purposes	0.09	0.08
Intra-industrial consumption	0.30	0.07
Total	7.91	7.77

Table 1: Production and use of blast furnace slag, 2024/2023 (in millions of tonnes; ABS, air-cooled blast furnace slag; GBS, granulated blast furnace slag)

Production	2024	2023
Slag from oxygen steel making	2.76	2.68
Slag from electric arc steel making	1.45	1.24
Others (SecMS, etc.)	0.46	0.49
Total	4.67	4.41

Use	2024	2023
Metallurgical use	0.52	0.46
Fertiliser	0.42	0.46
Construction material	2.13	2.03
Others	0.30	0.30
Sum	3.37	3.25
Final deposit	0.96	0.45
To interim storage	0.34	0.71
Total	4.67	4.41

Table 2: Production and use of steel furnace slag, 2024/2023 (in millions of tonnes; SecMS, secondary metallurgical slag)

was produced (2023: 11.4 million tonnes). In addition, a balanced total of 0.5 million tonnes of stock was reduced, meaning that a total of 11.3 million tonnes of ferrous slag could be marketed.

A differentiated analysis of material flows reveals that granulated blast furnace slag continues to account for almost 90% of total blast furnace slag production. Almost 99% of the granulated blast furnace slag was used for cement production, and existing interim storage facilities were depleted due to continuously high demand. This illustrates the importance of CEM II/S and CEM III cements containing granulated blast furnace slag for the cement industry as well as for the steel industry. These cements therefore continue to make a significant contribution to CO₂ savings in cement production.

Air-cooled blast furnace slag is primarily processed into aggregate mixtures for frost protection layers and gravel base courses, but also into aggregates for asphalt and concrete (approx. 0.2 million tonnes in 2024).

Steel furnace slag production amounted to 4.7 million tonnes in 2024 (previous year: 4.4 million tonnes), almost two-thirds of which came from the converter process. The use of products made from steel furnace slag rose slightly in 2024 compared with the previous year (3.4 million tonnes after 3.3 million tonnes in 2023), which is certainly also attributable to the construction industry. At 2.1 million tonnes (previous year: 2.0 million tonnes), the construction

materials market remains by far the most important sales segment in terms of volume. The use for Others (0.3 million tonnes) includes measures without formal quality control, e.g. use as construction material for landfill sites. Ultimately, 0.4 million tonnes of converter lime were used as high-quality fertiliser in agriculture, and around 0.5 million tonnes of steel furnace slag were used as lime and iron carriers in a resource-saving manner through internal recycling within the steel sites.

In total, 11.3 million tonnes of ferrous slag were used as construction materials and fertilisers in Germany in 2024. With a total production of 11.8 million tonnes, this continues to correspond to an exemplary high utilisation rate of 96%.

EUROPE

The European slag association EU-ROSLAG regularly asks its members for European slag data. Figures for 2024 are given in Tables 3 (blast furnace slag) and 4 (steel furnace slag). However, again in 2024 these figures must be qualified as it has not really been possible to obtain a satisfactory number of responses.

But based on the hot metal and crude steel production provided by Worldsteel [2], a respectable estimation of BFS production and SFS production can be made. This leads to about 19.6 million tonnes of BFS and 16.5 million tonnes of SFS produced in the EU-27 countries during the year 2024. The reported data provided in Tables 3 and 4 present about 73% of the BFS figures but only 55%

of the SFS figures. A comparison between the years 2024 and 2023 was made to illustrate the development, even if this is only of restricted validity. Comparing the production figures, there is a slight decline in production.

Comparing the percentages for BFS with those reported from Germany, the figures are quite close together: about 90% of the blast furnace slag is granulated, and for cement production additional slag must be taken from interim storage. Significantly smaller is the amount used as aggregate or aggregate mixtures for construction purposes. Only a very small amount is used for other purposes such as fertilising and glass production.

About two-thirds of the SFS produced is used for construction purposes, e. g. for roads, dams or hydraulic structures. About 10% is used for metallurgical purposes, 7% as fertiliser and a small percentage for other uses. Roughly 16% of the produced SFS was stored for future use or deposited finally.

In total the (reported) use is close to the (reported) production not only in Germany but also in most European countries. Steel-producing companies operating together with processing companies convert slag products in an example of the circular economy in working practice. <<<

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DEVELOPMENT OF QUENCHING PROCESSES FOR THE PRODUCTION OF MINERAL ABRASIVES FROM ACIDIC SLAG

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Background

INTRODUCTION

Abrasives are operating materials used in blasting technology and are employed in a wide range of applications, particularly for cleaning, de-rusting and de-coating metallic surfaces. One key area of application is the preparation of steel surfaces prior to the application of coatings that protect the steel from corrosive media such as moisture and salts [1][2][3]. Even small defects in the coating can lead to local corrosion, which can quickly spread to larger areas of the component during operation. Before applying new protective coatings, the existing coating must therefore be removed and the surface pretreated using suitable blasting methods, whereby non-metallic, i.e. mineral-blasting, agents are often used in practice.

Blasting with natural quartz sand, which was frequently used in the past, has been prohibited in Germany since 1975 – with a few narrowly defined exceptions – due to the high content of free crystalline silica and the associated risk of silicosis [4]. As a result, various mineral blasting agents became established, among which coal furnace slag (CFS), a by-product of coal-fired power generation, played a dominant role for many years as a cost-effective

disposable blasting agent. CFS is characterised by a wide range of applications and good physical properties for many blasting processes [5]. However, due to the restructuring of the energy sector, the promotion of renewable energies, and the resulting shutdown of coal-fired power plants, this material is increasingly only available in limited quantities and qualities [6].

Parallel to the declining availability of CFS, the market for blasting media has become significantly more differentiated [7]. In addition to metallic blasting media, a range of mineral products are used, including both natural raw materials and industrial by-products [8]. In line with the objectives enshrined in the German Closed Substance Cycle Waste Management Act (KrWG) of conserving natural resources and promoting the use of secondary raw materials, industrial by-products in particular are coming into focus as a potential raw material base for abrasives. These include, for example, nickel refinery slag, blast furnace slag and copper refinery slag, which are already being marketed to a limited extent as abrasives. However, there are restrictions on some of these materials in terms of availability, homogeneity or compliance with the normative requirements of the DIN EN ISO 11126 series of standards [9], so the need for suitable alternatives remains high.

The DIN EN ISO 11126 series of standards specifies the requirements for non-metallic abrasives used in the preparation of steel surfaces prior to the application of coating materials. For abrasives made from “iron and steel slags”, DIN EN ISO 11126-6 [10] specifies requirements for glass content, particle size distribution, apparent density, hardness, moisture content, water-soluble chlorides and water-soluble contaminants. The material must be predominantly vitreous amorphous material in order to prevent water absorption, and the content of free crystalline silica must not exceed 1% by mass. The grain sizes are typically in the range of about 0.2 mm to 2.8 mm, the apparent density in the range of about $2.6 \times 10^3 \text{ kg/m}^3$ to $3.9 \times 10^3 \text{ kg/m}^3$, and the hardness must be at least 6 on the Mohs scale. In addition, the moisture content of the end product must be limited, the electrical conductivity measured in the eluate, and the content of water-soluble chlorides must be regulated.

The importance of water-soluble salts for the durability of coating systems on steel is comprehensively documented in the technical literature [11][12]. Residual salts on the steel surface can draw water through the coating via osmotic effects, leading to local volume expansion, blistering and ultimately to the detachment of the protective layer [13]. In addition to chlorides, other water-soluble ions can also contribute to damage to the corrosion protection system [14], which means that, in addition to the specific determination of chlorides, the total conductivity parameter of the aqueous eluate is also used to assess the corrosion risk.

Against this backdrop, a wide variety of industrial by-products are gaining importance as potential raw materials for blasting media. One by-product that has not yet been established in the abrasive sector but is relevant in terms of quantity is cupola furnace slag (CFS) produced in foundries. Cupola furnaces are shaft furnaces that operate in a similar way to blast furnaces and are used in iron, steel and malleable iron foundries to melt pig iron and scrap into cast iron. Each melting batch produces about 5–10 percent by mass of slag, which is mainly collected in buckets, deposited in slag beds and, after slow cooling, processed into aggregates for road and path construction or as a substitute for landfill material, among other things. However, a significant proportion of CFS is landfilled, which is detrimental from both an ecological and economic point of view.

The chemical composition of CFS varies depending on the raw materials used and the products manufactured. Typically, CFS has a relatively low basicity with a CaO/SiO_2 ratio of between approximately 0.4 and 0.8, which in principle enables the formation of a high glass content under the right quenching (cooling) conditions. On the one hand, high glass content promotes properties that are desirable for abrasives, such as low water absorption and defined grain hardness; on the other hand, too high a glass content can lead to brittle, mechanically unstable products with insufficient hardness or promote fibre or wool formation, for which there is currently no technical use.

Previous research on CFS has focused primarily on its use in the cement industry, similar to granulated blast furnace slag, where the improvement of latent hydraulic properties was the main focus. The key requirements for abrasives – high hardness, low salt solubility and low conductivity of the eluate – were not the focus of attention. Preliminary investigations indicated that, despite factory cooling with higher glass contents, increased conductivity values may occur in the eluate in some cases, which can be attributed to an insufficient glass content or to concentrations of salts in the process water circulating in the system. The salt can then be precipitated on the slag.

Experience from previous research projects with blast furnace slag [15] and shaft furnace slag [16] shows that, by optimally adjusting slag composition and quenching, glassy products with sufficient hardness can be produced that consistently meet the requirements of DIN EN ISO 11126. One example of this is a blasting agent developed from special blast furnace slag, which has been successfully established on the market. These experiences form the basis for transferring the concept to cupola furnace slag, whereby the greater variability of CFS properties in foundry operations requires increased robustness of the processes.

Against this background, the aim of this research project was to develop a process for producing a glassy, mineral abrasive from cupola furnace slag that meets the technical requirements of DIN EN ISO 11126 for “iron and steel slags”. There is currently no separate standard for CFS abrasives. The development of a compact, high-performance quenching technology has resulted in a reproducibly hard abrasive with low

salt solubility, which opens up a wide range of applications in the surface preparation of steel.

METHODOLOGY

The research programme was divided into various work packages (WP), ranging from the basic characterisation of cupola furnace slag to the evaluation of blasting media properties under practical conditions.

WP 1: Sampling and slag characterisation

To identify possible production fluctuations, several batches were sampled from three foundries and supplemented with individual samples from other plants. The basic chemical characterisation included the determination of the main components using X-ray fluorescence analysis and the trace elements specified in the occupational safety regulations [17] after complete digestion (HF) followed by ICP-MS analysis. Chromium(VI) was determined in accordance with DIN EN 196-10 and reported as chromate. The mineralogical composition and the glass content were determined by X-ray diffraction and microscopic counting. The corrosive parameters for abrasives were determined in accordance with DIN EN ISO 11127-6/-7 [18] and [19] (water-soluble chlorides and electrical conductivity). Additional soluble anions were also examined. The apparent density, pure density, porosity and Mohs hardness were determined as technical parameters.

WP 2: Melting and quenching tests on a laboratory scale

For the melting tests, based on the results from WP 1, slags with significantly different basicity were se-

lected to cover the typical chemical range of CFS. The samples were melted in a Tammann furnace and set to a tapping temperature of 1,550°C. Initially, reference tests were carried out involving slow quenching and crystalline solidification to check for possible chemical changes. Various quenching methods were then tested (including preheated sand bed, Fe mould, steel and copper plates with and without cooling, water and dry granulation) (Figure 1) in a way that was designed to enable rapid quenching of the continuously flowing melt. The evaluation of the laboratory samples included basic tests based on WP 1.

WP 3: Operational tests on the cupola furnace

The operational tests were carried out on a cupola furnace in a foundry, whereby the cooling technology had to be integrated into ongoing operations without impairing casting production. For this purpose, a unit with a slightly inclined copper plate was used, onto which the liquid slag was fed in batches from the slag outlet and rapidly cooled by shaking during transport (Figure 2). The tests included slag from different operating phases (start-up, main and shutdown slag) and from two types of cast iron (GJL, GJS) in order to reflect the range of slag composition occurring in the plant. At the same time, samples were taken from the plant's own water-assisted cooling system in order to compare the new process with the established state of the art. The vitreous slag produced was characterised in the same way as in WP 1, and larger quantities were prepared for the subsequent blasting tests.



Figure 1: Tested quenching devices (from left to right): sand bed, iron mould, steel plates (uncooled), water granulation

WP 4: Blasting tests

The blasting tests were carried out in a modified blasting machine, which enabled the nozzle and sample surface to be positioned precisely, and the blasting agent used to be collected in its entirety (Figure 3). The glassy solidified CFS from the operational tests was used as the blasting material. Normal corundum, coal furnace slag and blast furnace slag were used for comparison. To evaluate the abrasive consumption, the abrasives were used several times, and the consumption was quantified, among other things, by means of sieve analysis of the undersized particles formed. The blasting performance was assessed using static image analysis of the blasted, painted steel surfaces, whereby digitised and binarized images were evaluated to determine the proportion of the surface that had been blasted clean. The resulting surface roughness of the de-coat-

ed samples was evaluated using standardised roughness comparison patterns in order to compare the surface finish achieved with that of established blasting media.

RESULTS

Results WP 1 – Sampling and characterisation

The 19 initial samples have basicities between 0.4 and 1.2, with the majority of the slags tending to be in the acidic range, which favours glassy solidification. The trace element and free crystalline silica contents are low overall, in compliance with occupational safety limits (Table 1).

The leaching tests in accordance with ISO 11127-6/7 show that water-soluble chlorides are generally present in low concentrations and that the limit values of the ISO 11126 series of standards are complied with in most cases. However, the electrical conductivity of

the eluates (water-soluble contaminants) sometimes exceeds the required value, particularly due to dissolved sulphates (Table 2).

A direct, clear correlation between glass content and salt solubility cannot be deduced from the initial samples, as both low and high conductivities were measured at high glass contents (Figure 4). The technical parameters vary significantly: depending on the plant, the Mohs hardness is sometimes below 6, the apparent density varies between 1.8 and 2.9 kg/dm³, and the glass content ranges from 26% to 100% by volume. Samples with high porosity in particular have lower densities and thus unfavourable blasting properties, which underlines the need for a targeted quenching process to stabilise quality.



Figure 2: Pouring a ladle sample onto the copper vibrating chute (left) and removed and already cooled slag samples at the end of the blast chute (right)



Figure 3: Positioning of the blasting gun and the blasted surface in the test box (left)

Table 1: Minimum, maximum and average values for the solid content and mineralogy of the 19 cupola furnace slags examined (initial samples)

Parameter	Unit	Min.	Max.	Mean
Al ₂ O ₃	wt. %	7.28	17.40	10.45
CaO		21.3	43.4	34.41
FeO		0.18	5.32	1.18
K ₂ O		0.67	0.46	
MgO		0.81	2.79	1.52
MnO		0.79	6.15	3.26
Na ₂ O		0.21	0.69	0.38
P ₂ O ₅		0.01	0.03	0.02
SiO ₂		36.10	55.20	46.30
S _{total}		0.07	0.87	0.25
TiO ₂		0.24	1.11	0.52
TC		0.02	0.80	0.11
TIC (as CO ₂)		0.01	0.66	0.09
As		mg/kg	0.34	2.10
Be	2.40		7.70	3.61
Cd	< 0.01		0.40	0.08
Co	1.41		78.40	22.72
Cr VI	< 1.00		1.00	< 1.00
Ni	2.20		14.80	5.17
Pb	0.20		1.50	0.58
Sb	0.10		0.20	0.17
Sn	0.27		9.59	2.18
Basicity	-		0.40	1.20
Free crystalline silica:				
Quartz	wt. %	< 1	1.8	< 1
Cristobalite		< 1	< 1	< 1
Tridymite		< 1	< 1	< 1

Results WP 2 – Melting and quenching tests on a laboratory scale

Remelting in the Tammann furnace leads to slight shifts in the chemical composition. Even the refer-

ence cooling in the muffle furnace causes a change in salt solubility compared to the original samples, meaning that the conductivity and sulphate content decrease for three of the four slags examined, while

Table 2: Statistical evaluation of the salt solubility of the 19 initial samples examined (grain size 1/2 mm) in accordance with ISO 11127-6 and -7

Parameter	Unit	Min.	Max.	Average	Requirement ISO 11126-6
Conductivity of the aqueous eluate	µS/cm	31	855	263	250
Water-soluble chlorides	%	0.00007 (0.7 mg/l)	0.0062 (62 mg/l)	0.0017 (17 mg/l)	0.0025 (25 mg/l)
Water-soluble sulphate	%	0.0001 (0.1 mg/l)	0.0268 (268 mg/l)	0.0067 (67 mg/l)	-

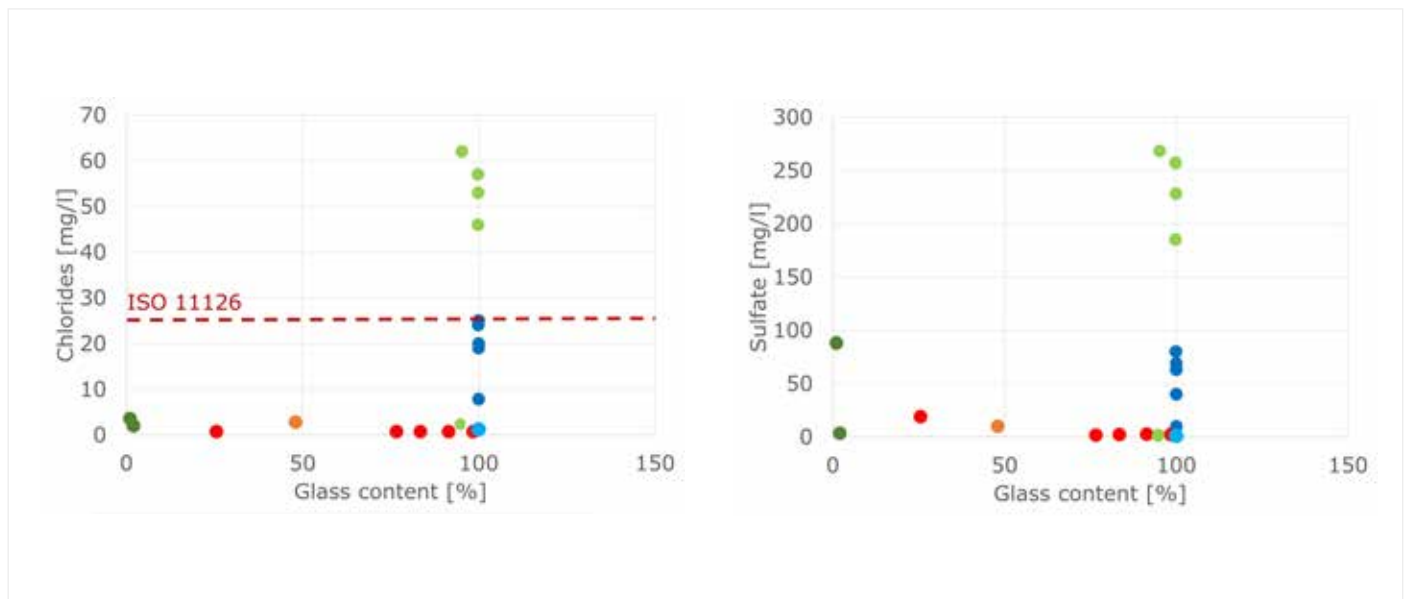


Figure 4: Chloride concentration (left) and sulphate (right) concentration of the 19 initial samples according to ISO 11127-6 and -7, respectively, as a function of glass content

an increase is observed in one sample. The reference samples with slow cooling are predominantly crystalline and have low glass contents but serve as a basis for comparison with the rapid quenching methods.

The quenching variants examined produced glassy or glassy-amorphous products for all slags, with casting into preheated iron moulds already yielding satisfactory glass content. Processes with a particularly high cooling rate (turntable, water bath, water granulation) result in highly glassy but brittle products that tend to form strands and have a high proportion of undersized particles during processing that cannot be used as blasting media. Although the sand bed produces glassy slags, it is unsuitable for practical use due to quartz sand adhesion. Overall, conductivity (Figure 5) and sulphate concentrations decrease in many rapidly quenched samples compared to the original and reference states. Only a few combinations (turntable, water granulation) show an increase. All samples produced on a laboratory scale meet the requirements of the ISO 11126 series with hardnesses ≥ 6 according to Mohs, confirming the basic suitability of rapidly cooled CFS as a blasting agent.

Results WP 3 – Operational tests on the cupola furnace

As expected, the slag quenched to a glassy state in the plant using the copper vibrating chute shows only slight variations in solid content compared to the

plant's own cooled samples. At an average of around 0.9, the basicity remains within the favourable range for glassy solidification. Only moderate differences in solid content can be observed between the various operating phases and cast-iron types (GJL, GJS); therefore, a constant slag quality can be assumed. Visually, the samples differ significantly. While the factory-cooled slag exhibits visible multi-colouration and thus inhomogeneity despite its high glass content, the samples quenched via the copper vibrating chute appear uniformly black and shiny (Figure 6). X-ray phase analyses confirm that all the slags examined – both from the plant's own cooling system and from the new cooling route – are amorphous and do not contain any free silicic acid.

On the day of the operational tests, the CFS from the plant's own cooling system already met the requirements of the ISO 11126 series for all parameters examined. Therefore, hardly any differences could be detected between the samples from the operational tests with regard to water-soluble salts. One significant difference, however, is porosity. The slag produced via the copper vibrating chute has hardly any pores, while the factory's own slag has slightly higher porosity. Overall, it can be seen that the selected cooling technology can achieve uniform, standard-compliant blasting media quality on an industrial scale, although reliable statements on slag with exceptionally high salt loads are still pending.

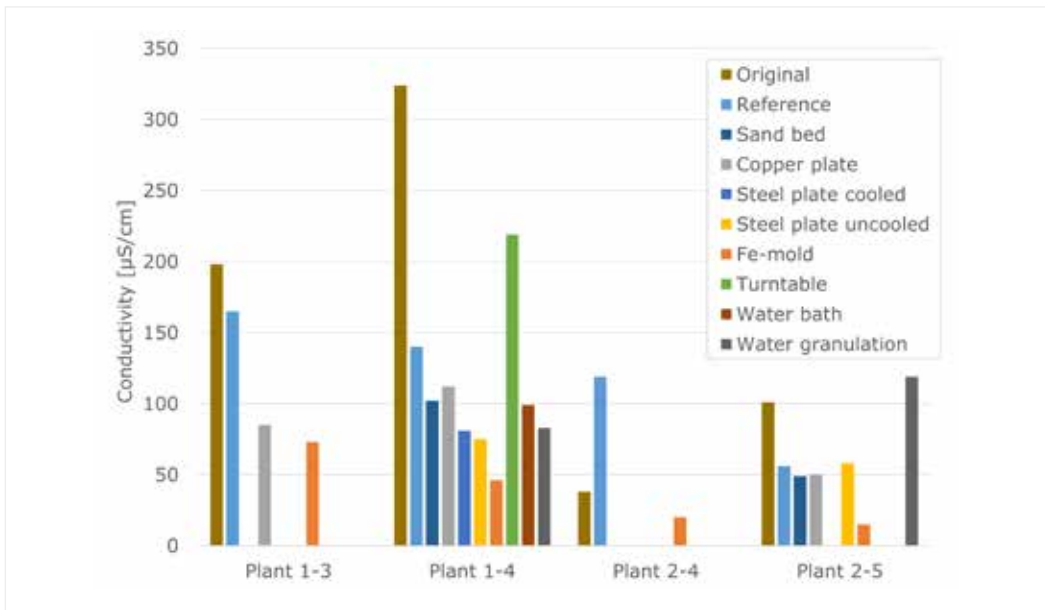


Figure 5: Electrical conductivity after the melting tests compared to the original and reference tests according to ISO 11127-6 and -7

Results WP 4 – Blasting tests

The blasting tests prove that vitrified cupola furnace slag is comparable to established blasting media in terms of wear and blasting performance. The undersized fraction of CFS produced after three blasting passes is around 8.3–10.4%, which is on a par with the reference materials normal corundum (NC) and blast furnace slag, although comparison with melting chamber granulate is only possible to a limited

extent due to a different initial grain size (Figure 7). The average grain sizes determined after use are in the range of the reference materials for CFS and indicate typical wear behaviour acceptable for disposable blasting media.

Static image analysis of the de-coated, painted steel surfaces shows that the surfaces blasted with CFS are in the range of the reference blasting media BFS



Figure 6: Photo of the main slag GJL from the plant's own cooling system (left) and from the operational test (right)

and CF, with the exception of one sample from the factory’s own cooling system. Comparable de-coating performance is achieved in particular with the slag produced in the operational test. The factory-cooled GJL sample, on the other hand, performs significantly worse and achieves the smallest de-coated area (Figure 8). The evaluation of roughness shows that all blasting media tested have predominantly medium roughness in the range of 50–70 µm, supplemented by edge areas with fine roughness of around 23–28 µm. This allows a blasting pattern to be produced that can compete with the mineral blasting media established on the market in terms of surface profile and de-coating.

formation of glassy structures, which are essential for meeting the normative requirements for non-metallic blasting media. Restrictions arise, among other things, for the parameters of hardness and salt solubility. It follows that cupola furnace slag has great potential as a raw material for blasting media, but this potential can only be exploited with controlled process management and targeted conditioning.

The development of a special quenching unit is a key starting point for this. Laboratory tests show that dry metallic cooling surfaces deliver reproducible glassy products that meet the requirements of the standard. The transfer of this principle to an indus-

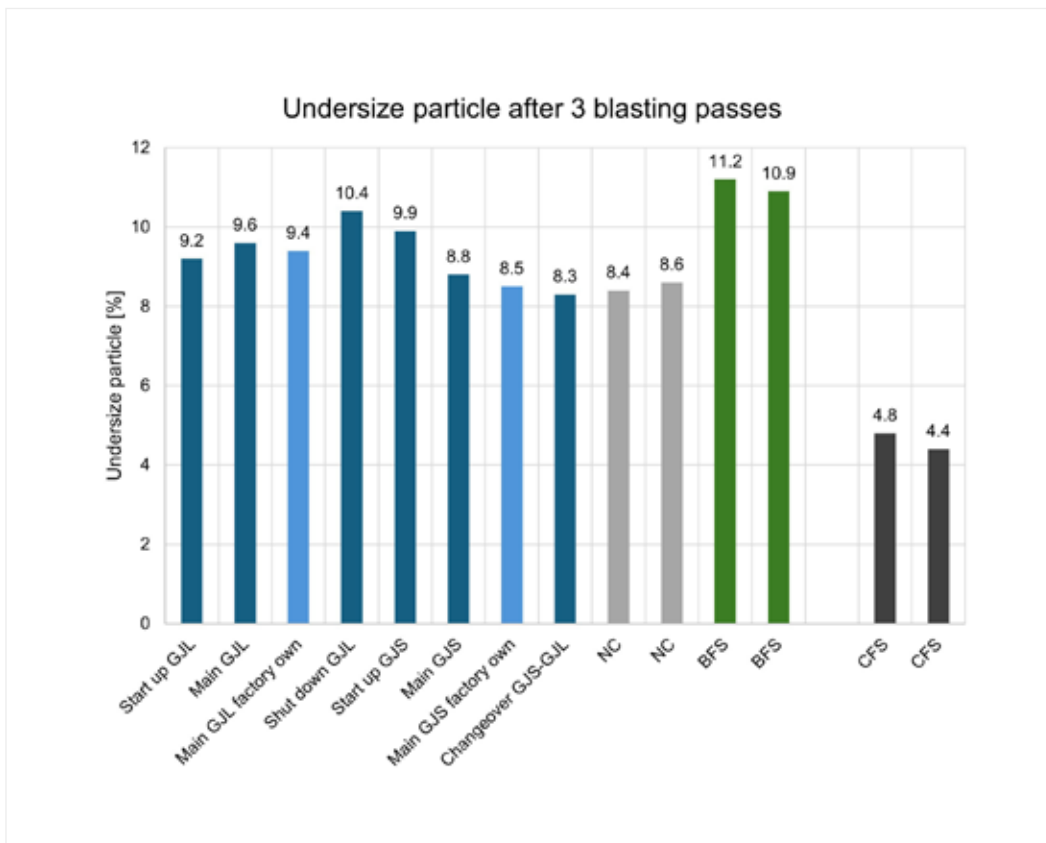


Figure 7: Proportion of undersized particles <0.5 mm and <0.2 mm (CFS) after 3 blasting passes

EVALUATION/DISCUSSION

Based on the investigations, cupola furnace slag has proven to be a fundamentally suitable raw material for mineral disposable blasting media, provided that the chemical composition, cooling/quenching and processing are specifically adjusted. The predominantly low basicity of the raw slag promotes the

trial scale in the form of a copper vibrating chute has been successfully demonstrated under real foundry conditions. The plant produced uniformly glassy, dense and homogeneously solidified slag with low porosity and salt solubility. In contrast, the plant’s own cooling system also produces predominantly glassy products, but with significant inhomogeneities

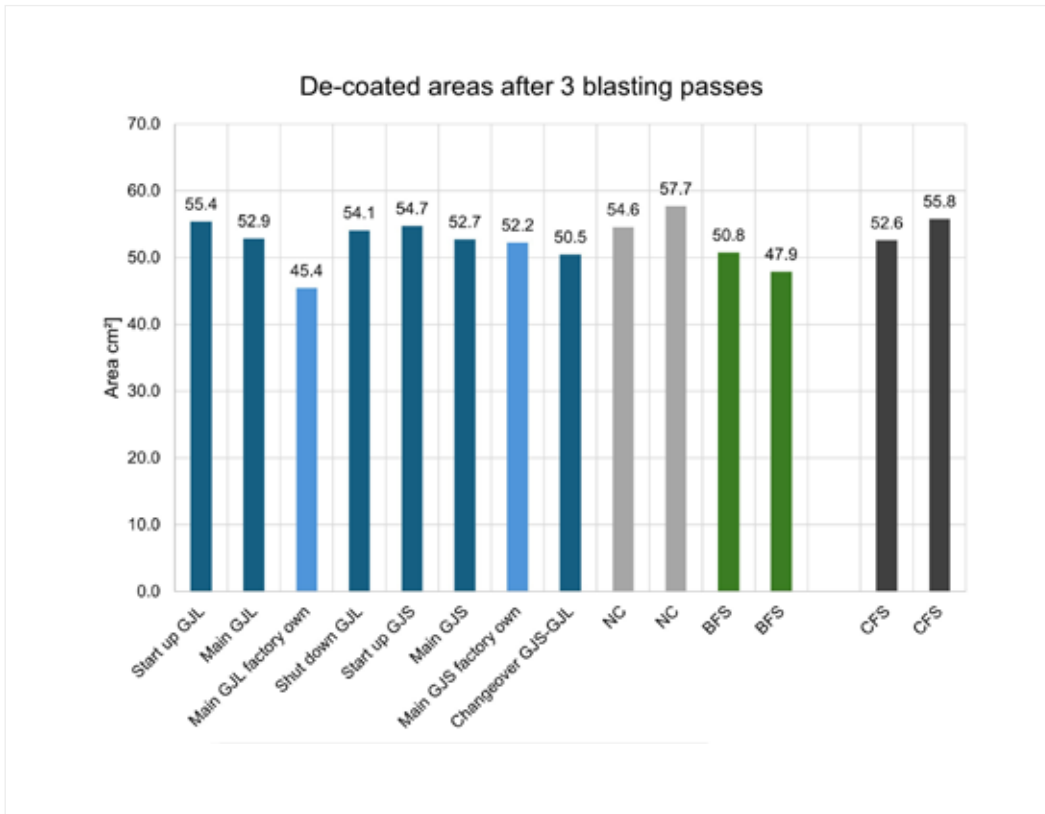


Figure 8: De-coated areas after the blasting tests, indicated as area

and increased porosity. The results of the operational tests show that the technology developed can be used to produce homogeneous slag qualities.

The blasting evaluation of vitrified cupola furnace slag shows that it is largely comparable to established blasting media such as melting chamber granulate, blast furnace slag and normal corundum in terms of blasting pattern, removal rate and grain wear. The blasted surfaces and the surface roughness achieved are in the same range as those of the reference materials. Significant limitations in practical use are therefore not to be expected. The observed wear of the CFS grains (under-grain formation of typically 8–10% after several blasting passes) is slightly higher than that of very hard reusable blasting media but is within the range of conventional disposable blasting media and can be economically compensated for by the significantly lower costs. The lower porosity of the grains produced with the copper vibrating chute is another advantage, as it tends to result in lower water absorption and higher breaking strength. In a direct comparison, slag from the factory's own cooling system performs slightly worse on average in terms

of both de-coating performance and grain stability, which underlines the importance of controlled cooling for ensuring consistent blasting media quality.

CONCLUSION

Glassy solidified cupola furnace slag (CFS) has proven to be a technically suitable raw material for mineral disposable blasting media. The contents of free crystalline silica and trace elements largely meet occupational health and safety requirements but require specific process control in terms of salt solubility. Rapid cooling on a copper vibrating chute has proven itself on a laboratory scale and in foundry operations, producing reproducible glassy slag with Mohs hardness ≥ 6 , high glass content and low porosity. Blasting tests show that CFS-based blasting media are comparable to commercially available products in terms of surface removal, surface roughness and grain wear, and have advantageous water absorption and breaking strength properties due to their low porosity.

The methodology already used in previous research projects to develop cooling processes for the pro-

duction of abrasives from industrial by-products was successfully refined in this research project and could also be transferred to other raw materials in a similar way.

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