

Data-driven modeling and experimental validation of heat-resistant concrete for industrial furnace lining

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Received 19 April 2025; accepted 5 May 2025; published online 15 May 2025

DOI <https://doi.org/10.21595/vp.2025.25013>



72nd International Conference on Vibroengineering in Almaty, Kazakhstan, May 15-16, 2025

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Abstract. The purpose of this study is to extend the service life of liquid-layer furnaces through experimental evaluation of their performance. Instead of using conventional large and small aggregates, this research investigates the use of secondary refractory materials to reduce the cost of the concrete mixture. To address this problem, it was proposed to replace the traditional method of lining the furnace floor with SHB-brand fireclay bricks by a monolithic concrete structure. Considering the operational characteristics of the furnace - high temperatures up to 1000 °C and an aggressive environment producing SO₃ gaseous sulfur -sodium-infused liquid glass concrete was selected as the base. Instead of cement, liquid glass with low thermal conductivity, including amorphous-phase materials and glass-layered composite viscous substances, is recommended. A novel aspect of this research is the integration of machine learning techniques with experimental data to predict the thermal performance of concrete under high-temperature conditions. Furthermore, the study introduces the use of secondary refractory materials as a cost-effective aggregate alternative, offering a unique combination of sustainability and performance in industrial furnace applications.

Keywords: fluidized bed furnace, heat-resistance concrete, fire-resistance concrete, lining, secondary refractories.

1. Introduction

The increasing construction of various thermal units and load-bearing structures that operate under simultaneous exposure to high (both constant and variable) temperatures and aggressive environments requires the development and use of heat-resistant and chemically resistant materials. It also necessitates the creation of new construction techniques that can extend the service life of thermal units while supporting industrial-scale construction [1, 2].

Fluidized bed furnaces are one such type of thermal unit that operates under extreme conditions of continuous high temperature and chemically aggressive environments. Currently, these furnaces are typically lined with fireclay refractories [3].

The lower chamber is lined with three layers of bricks, while the upper chamber uses only half a brick. To maintain the gas temperature necessary for particle oxidation, the upper part of the working chamber is additionally insulated with lightweight fireclay or diatomaceous earth refractories (40-70 mm thick), often combined with asbestos layers [4].

The furnace bottom is constructed from heat-resistant concrete based on liquid glass or

Portland cement, formed into a slab or arch 200-300 mm thick with openings for gas nozzles. The roof, arched loading chamber, and discharge zones are also lined with fireclay refractory [8, 9].

A common issue during furnace operation is the poor quality of lining works. Presently, the shaft walls and furnace dome are lined with Category I fire-resistant masonry, while the furnace bottom is filled with heat-resistant concrete [15]. Several deficiencies have been identified in lining materials [8, 9]. These include the use of mastic with lower density than brick, leading to ejection from joints; improper construction sequence (pouring concrete after building the walls); and concrete shrinkage at high temperatures, resulting in cracking and even melting of the furnace's steel base. Air leakage between the lining and steel structure also disrupts fluidized bed formation, requiring increased air supply [6]. Additionally, insufficient expansion joints – often just a single 5 mm asbestos sheet – are ineffective in winter, leading to deformation or rupture of the furnace shell [2].

Such failures compromise the zinc production process, lowering SO_2 concentration in exhaust gases, increasing oxygen demand, and ultimately reducing the quality of cathode zinc [10]. A key challenge in non-ferrous metallurgy is increasing the productivity of fluidized bed roasting furnaces by extending their lifespan [11]. To achieve this, the replacement of traditional piece-based lining with monolithic concrete is proposed. However, it must first be proven that heat-resistant concrete meets all technical requirements for such environments [12].

These environments are characterized by temperatures up to 1000 °C and exposure to sulfur dioxide (SO_3). Among the known options, sodium-infused liquid glass concrete with sodium silicofluoride additives offers both heat and chemical resistance [9]. This composition was selected as the base for the current research.

Unlike previous studies that focused solely on experimental testing, this study combines physical experiments with data-driven machine learning modeling to predict material behavior under high-temperature conditions.

The computational methods applied here, similar to GIS-based optimization techniques, enhance data processing capabilities and enable effective decision-making in the design of concrete mixes for extreme environmental conditions [13].

The relevance of this topic lies in its potential to increase furnace productivity by minimizing downtime for repairs.

2. Materials and methods

Heat-resistant concrete is currently used in both prefabricated components and monolithic structures. Industrial applications include multipod furnaces for sulfur pyrite roasting, coarse dust collectors, dust chambers, ABM-1.5A unit covers, trolleys of tunnel kilns, and furnaces with fluidized beds [5].

The proposed monolithic lining design for the fluidized bed furnace consists of a cylindrical steel shell insulated with several layers of asbestos cardboard. This is followed by a layer of monolithic heat-resistant concrete on liquid glass, reinforced with steel mesh in the walls and a spatial steel frame in the dome [7]. The hearth is also filled with heat-resistant concrete, where steel nozzles serve as reinforcement [14].

The new lining design was developed in accordance with the national standards of the Republic of Kazakhstan and relevant international guidelines. Multi-criteria analysis techniques similar to those used in flood-hazardous area determination [24, 25]. were considered when selecting and optimizing structural parameters for thermal loads. The required thickness of the protective concrete layer was determined based on both regulatory requirements [15, 16]. and experimental data [15, 16].

An innovative patent (No. 28370) from the Republic of Kazakhstan was granted to the design team for this monolithic lining concept. A distinctive feature of the concrete composition is the use of crushed SHCU fireclay bricks as coarse and fine aggregates. These were sourced from the firebrick lining of Welz furnaces and crushed to specific fractions, following the

intergovernmental standard GOST 20910-2019 [17, 18].

The primary objective in developing the concrete mix was to determine the optimal ratio between fine and coarse aggregates to minimize binder consumption. This approach aimed to reduce porosity and shrinkage while enhancing the refractory properties of the concrete [19].

The total porosity of concrete based on liquid glass depends on the porosity of the aggregate, which can be reduced by impregnation with liquid glass. It also depends on the porosity of the hardened binder and on voids between aggregate grains. Lower porosity contributes to increased strength and resistance to both high temperatures and aggressive environments [20].

Another key factor in the performance of heat-resistant concrete is temperature-induced shrinkage, which is primarily influenced by the binder content. The more binder used, the greater the shrinkage. To address this, binder content should be minimized. In many cases, the binder is also less refractory than the aggregate, making its reduction even more desirable.

The concrete mix design was based on the method developed by F. I. Melnikov. The core principle is to ensure that the voids between aggregate grains are filled with excess binder paste, sufficient to provide proper workability and to compensate for absorption by porous aggregates [21-23].

3. Results and discussions

Two series of concrete samples, “1 from 12.07” and “4 from 16.07”, were tested to assess their thermal resistance. The results showed that the “1 from 12.07” series - with the majority of samples - endured 12 to 14 heating cycles at 900 °C. This confirms its compliance with SN 156-67 standards for heat-resistant concrete. In contrast, the “4 from 16.07” series withstood only 1 to 2 cycles, although at 800 °C it showed acceptable performance.

The reduced thermal performance of the “4 from 16.07” samples is attributed to the inconsistent quality of the liquid glass used in their composition. Different production batches of liquid glass were used for the two sample series. The thermal resistance results are presented in Table 1, and visual observations of the samples after testing are shown in Figs. 1-3.



Fig. 1. Appearance of sample series “1 from 12.07” after testing at 900 °C



Fig. 2. Appearance of sample series “4 from 16.07” after testing at 900 °C

To evaluate compressive strength, two additional series “2 from 13.07” and “3 from 13.07” were prepared, each consisting of three cubes with 100 mm sides. Testing was carried out on an MS-500 hydraulic press.

Prior to testing, the samples were weighed and their actual dimensions recorded. The samples were then subjected to compressive loading until complete failure [7, 8].

The characteristic compressive strength was calculated using Eqs (1):

$$R_b(n) = R_b(28) \cdot \frac{\ln 28}{\ln n}. \tag{1}$$

(1) $R_b(n)$ and $R_b(28)$ represent the ultimate strength of concrete after n and 28 days, respectively, in kg/cm^2 ; $\ln(n)$ and $\ln(28)$ are the natural logarithms of the corresponding curing times.

The compressive strength results are summarized in Table 2, and photographs of the testing process are shown in Fig. 4.



Fig. 3. Appearance of sample series “1 from 12.07” after testing at 1200 °C

Table 1. Thermal stability of heat-resistant concrete

No. p/p	Dimensions of samples, mm	Weight of samples, g	Volume weight of samples at the time of testing, kgs/m³	Age, day	Number of heat changes of the sample, Rts air, 900°C	Average number of heat changes in a series of samples, Rts
Heat-resistant concrete No. 1						
1	70	610	1780	90	12	12,5
2	70	640	1870		12	
3	70	640	1870		12	
4	70	650	1900	94	12	
5	70	660	1920		14	
6	70	670	1950		13	
Heat-resistant concrete No. 4						
4	70	640	1870	93	2	1,3
5	70	690	2010		1	
6	70	690	2010		1	

As shown in Fig. 5, the data illustrate a comparative analysis of heating cycles and compressive strength across the tested concrete samples.

Concrete No. 1 exhibited significantly greater thermal stability than Concrete No. 4, withstanding up to 14 cycles at 900 °C in accordance with SN 156-67. Concrete No. 4, by contrast, withstood only 1–2 cycles, indicating its unsuitability for high-temperature use. This poor performance is linked to the inferior quality of liquid glass used in its formulation.

Concrete No. 2 and No. 3 showed high compressive strength values ranging from 250 to 273 kg/cm^2 , indicating excellent load-bearing capacity. The consistency of results between the two series suggests that the sodium liquid glass-based composition provides both thermal and mechanical reliability when properly formulated.

To deepen the understanding of how physical properties influence heat resistance, a machine learning model using linear regression was developed. Input features included sample weight, volume density, and curing age. A similar application of GIS technologies for data-driven

environmental analysis was demonstrated in industrial regions of Ust-Kamenogorsk [25], which supports the relevance of such computational approaches in industrial material performance research.

The model achieved an R^2 value of 0.47, indicating a moderate ability to predict the number of heating cycles at 900 °C.

Despite the limited dataset, these findings highlight the potential of data-driven approaches to optimize the design of heat-resistant concrete mixtures.

Table 2. Compressive strength of heat-resistant concrete

No. p/p	Dimensions of samples, mm	Weight of samples, g	Volume weight of samples at the time of testing, kgs/m³	Age, day.	Strength of samples during testing, kgs / cm²	Strength of concrete during testing, kgs/cm²	Calculated value of brand strength, kgs / cm²
Heat-resistant concrete No. 2							
1	100×99×103	1960	1922	83	250,47	270,45	203,94
2	102×100×101	1990	1932		273,40		
3	105×100×101	1995	1881		267.49		
Heat-resistant concrete No. 3							
4	104×101×102	1990	1858	83	262,90	269,53	203,25
5	102×101×101	1980	1903		266,98		
6	105×100×103	2025	1872		272,08		



a) Sample series “2 from 13.07” and “3 from 13.07”



b) Compression testing on the MS-500 press

Fig. 4. Photos of cube strength tests

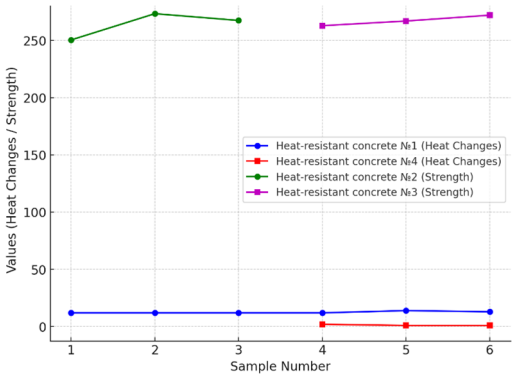


Fig. 5. Comparison of thermal cycles and compressive strength of heat-resistant concrete samples

4. Conclusions

The experimental study confirmed the feasibility of using secondary refractory materials as aggregates in the production of heat-resistant concrete. This approach offers a cost-effective alternative by reducing the consumption of primary raw materials. By optimizing the concrete composition, including the replacement of cement with sodium-based liquid glass and the use of

crushed SHCU fireclay bricks, improvements in both thermal resistance and compressive strength were achieved. Test results demonstrated that certain compositions could endure up to 14 heat cycles at 900 °C, meeting industrial furnace requirements.

Furthermore, machine learning analysis was employed to model the relationship between physical parameters (such as weight, density, and curing age) and thermal performance. The regression model showed that data-driven approaches can provide useful predictions for material behavior, especially in variable high-temperature environments.

These findings contribute to the development of standards for heat-resistant concrete and offer practical guidance for engineers and designers working on furnace lining systems. The proposed monolithic lining method reduces the number of joints, enhances durability in aggressive environments, and shortens repair times, thereby improving operational efficiency in industrial applications. The combination of experimental validation and machine learning analysis represents a novel methodological contribution, enabling more accurate design of durable, high-performance concrete for industrial furnace applications.

Acknowledgements

The authors have not disclosed any funding.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflict of interest

The authors declare that they have no conflict of interest.

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