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Blast Furnace Slag as an Alternative to Natural Mineral Materials in Pavement Engineering: A Review

[1]Kunaev V.A., [1]Akhmetova G.E., [1*]Ospanova A.Z., [1]Kenzhaliyev O.B., [1]Tavshanov I.S., [2]Fathi M.S., [1]Ulyeva G.A., [1]Batyrbek A.E., [1]Charnyi D.Yu.

[1] *Karaganda Industrial University, Karaganda region, Temirtau, Kazakhstan*
[2] *Universiti Teknologi Malaysia, Kuala Lumpur, Malaysia*

** Corresponding author email: a.ospanova@tttu.edu.kz*

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ABSTRACT
The presented literature review contains the results of the analysis of scientific articles for 2000-2026 years, considering the use of blast furnace slag in various areas of road construction. It has been established that there are clear differences between the application options for different types of blast furnace slag. Air-cooled blast furnace slag (ACBFS) is more often used as a coarse or fine aggregate for cement concrete and asphalt concrete, and ground granulated blast furnace slag (GGBFS) is used as an additional binder or as a mineral/reactive filler. When using blast furnace slag in the production of concrete, the highest results in a number of studies were achieved when replacing 20-40% of the aggregate with slag, although this indicator was not a universal optimal value. In some articles, it was pointed out that the use of blast furnace slag as part of the base of a highway or for soil stabilization was associated with an increase in CBR. Some authors point to a reduction in the consumption of Portland cement when using complex binders containing granular blast furnace slag. Data on the improvement of water resistance, fatigue resistance, Marshall stability, and rutting resistance of asphalt concrete with the introduction of ACBFS and GGBFS in various proportions are also presented. Pretreatment of porous ACBFS was also important: selective crushing and related separation methods reduced water absorption, crushing value, and the proportion of weak porous particles. The main practical conclusion is that BFS should not be treated as a single interchangeable material. Its use should be selected according to slag type, particle quality, the component being replaced, and the required pavement property. Further studies should examine whether improvements achieved by slag pretreatment at the aggregate level are retained in concrete, asphalt mixtures, and pavement-base materials under long-term service conditions.

Keywords: air-cooled blast furnace slag, ground granulated blast furnace slag, natural mineral resource substitution, aggregate enrichment, cement concrete, asphalt concrete, pavement base materials.

Information about authors:

Kunaev Vyacheslav Alexandrovich	*PhD, Associate Professor, Director of the Department of Science and Innovations, Karaganda Industrial University JSC, Republic Ave., 30, 101400, Temirtau, Karaganda region, Kazakhstan. E-mail: v.kunayev@tttu.edu.kz; ORCID ID: https://orcid.org/0000-0001-8283-7186*
Akhmetova Gulzhainat Esenzholovna	*PhD, Associate Professor, Karaganda Industrial University JSC, Republic Ave., 30, 101400, Temirtau, Karaganda region, Kazakhstan. E-mail: agulzhajnat@bk.ru; ORCID ID: https://orcid.org/0000-0001-8244-5027*
Ospanova Ayaulym Zaynullaevna	*PhD student, Karaganda Industrial University JSC, Republic Ave., 30, 101400, Temirtau, Karaganda region, Kazakhstan. E-mail: a.ospanova@tttu.edu.kz; ORCID ID: https://orcid.org/0009-0002-0597-1220*
Kenzhaliyev Olzhas Bagdauletovich	*PhD, docent, Karaganda Industrial University JSC, Republic Ave., 30, 101400, Temirtau, Karaganda region, Kazakhstan. E-mail: o.kenzhaliyev@tttu.edu.kz; ORCID ID: https://orcid.org/0000-0002-3776-9724*
Tavshanov Ilgar Suleimanovich	*Researcher, Karaganda Industrial University JSC, Republic Ave., 30, 101400, Temirtau, Karaganda region, Kazakhstan. E-mail: i.tavshanov@tttu.edu.kz; ORCID ID: https://orcid.org/0000-0002-9427-9748*
Fathi Mohamad Syazli	*PhD, Associate Professor, Universiti Teknologi Malaysia, Jalan Sultan Yahya Petra, 54100, Kuala Lumpur, Malaysia. E-mail: syazli@utm.my; ORCID ID: https://orcid.org/0000-0002-0474-6278*
Ulyeva Gulnara Anatolyevna	*PhD, Professor, Karaganda Industrial University JSC, Republic Ave., 30, 101400, Temirtau, Karaganda region, Kazakhstan. E-mail: g.ulyeva@tttu.edu.kz; ORCID ID: https://orcid.org/0009-0002-7300-1277*
Batyrbek Alibek Yesimbekuly	*PhD student, Karaganda Industrial University JSC, Republic Ave., 30, 101400, Temirtau, Karaganda region, Kazakhstan. E-mail: a.batyrbek@tttu.edu.kz; ORCID ID: https://orcid.org/0000-0002-3369-6804*
Charnyi Dmitryi Yurievich	*Junior Researcher, Karaganda Industrial University JSC, Republic Ave., 30, 101400, Temirtau, Karaganda region, Kazakhstan. E-mail: dmitryi.charnyy@gmail.com; ORCID ID: https://orcid.org/0009-0005-9438-2330*

Introduction

Road construction requires large volumes of natural aggregates and cementitious materials. At the same time, metallurgical production generates mineral by-products that can partly replace these conventional resources. Blast furnace slag (BFS) is one of the most widely studied materials of this type and is used in concrete, pavement layers, soil stabilization, and asphalt mixtures [[1], [2], [3], [4], [5], [6]].

The physical and mechanical properties of blast furnace slag largely depend on the cooling method. Slow air cooling produces air-cooled blast furnace slag (ACBFS), which is mostly crystalline, angular, and often porous and is used primarily as a coarse or fine aggregate. During rapid cooling, granulated blast furnace slag (GBFS) is formed, which has a higher content of the glassy phase. After grinding, GBFS is converted into ground granulated blast furnace slag (GGBFS), which exhibits latent hydraulic activity and is used mainly as a supplementary cementitious material or as a mineral or reactive filler [[7], [8], [9], [10], [11]]. The differences in the appearance and microstructure of ACBFS and GBFS are shown in Figure 1. The porous structure of some ACBFS fractions may increase water absorption and reduce resistance to cyclic environmental effects, whereas denser or processed slag fractions can show substantially better engineering properties [[6],[12], [13], [14], [15]].

Published studies address several distinct applications of BFS, including aggregate replacement in cement concrete, partial replacement of cement by GGBFS, use in pavement bases and subbases, soil stabilization, and incorporation into asphalt mixtures. Direct comparison of these studies is difficult because the term “BFS replacement” may refer to replacement of coarse aggregate, fine aggregate, cement, total binder, or mineral filler. In addition, the studies differ in slag type, dosage basis, treatment method, mixture composition, curing conditions, and performance criteria. As a result, replacement percentages reported in different studies cannot be interpreted independently of the function of the slag in the material.

Figure 1 – General view and SEM images of blast-furnace slag: a) air-cooled blast-furnace slag (ACBFS); (b) SEM micrograph of ACBFS; (c) granulated blast-furnace slag (GBFS); and (d) SEM micrograph of GBFS

The aim of this review is to compare the reported use of ACBFS, GBFS, and GGBFS in road construction materials and to identify the main relationships between slag type, processing method, replacement level, and engineering performance. Particular attention is given to cement concrete, cementitious systems, pavement bases and subbases, soil stabilization, and asphalt mixtures. The review also examines the limitations associated with untreated slag and the effect of processing and modification on its potential use in pavement materials

Materials and methods

The literature search covered publications issued between 2000 and 2026 and was completed on 25 July 2026. The main search was conducted in Scopus, Web of Science, ScienceDirect, and eLIBRARY.RU. ResearchGate and Academia.edu were used as additional sources for locating full-text publications. The search was based on a combination of terms describing blast furnace slag and its application in road and construction materials. The following search expression was used: (“blast furnace slag” OR “GGBFS” OR “ACBFS”) AND (“pavement” OR “asphalt concrete” OR “road construction” OR “cementitious composites”).

The search expression was adapted to the syntax of the individual databases while retaining the same set of keywords and the same publication period. The reference lists of relevant publications were also examined to identify additional studies that could be useful for the analysis.

The database search identified a total of 1120 records published between 2000 and 2026. At the title and abstract screening stage, 370 records were excluded because their subject matter was outside the scope of the review. Of the remaining 750 records, full-text versions were available for 342 publications. The full texts were subsequently assessed with regard to the subject of the study, the type of slag investigated, the presence of an experimental component, and the availability of quantitative results suitable for comparative analysis.

After the full texts were checked, 262 publications were removed from the final sample. The main reasons were the absence of experimental work, the lack of separately reported data for blast furnace slag, insufficient experimental detail, or a topic outside the scope of this review. Publications that could not be obtained in full text were not included in the detailed assessment.

The final set included 80 publications: 77 primary research papers and three review articles. The quantitative comparisons in this review are based mainly on the primary studies. The three review papers were used only for background information, terminology, general research trends, and for identifying additional primary studies from their reference lists.

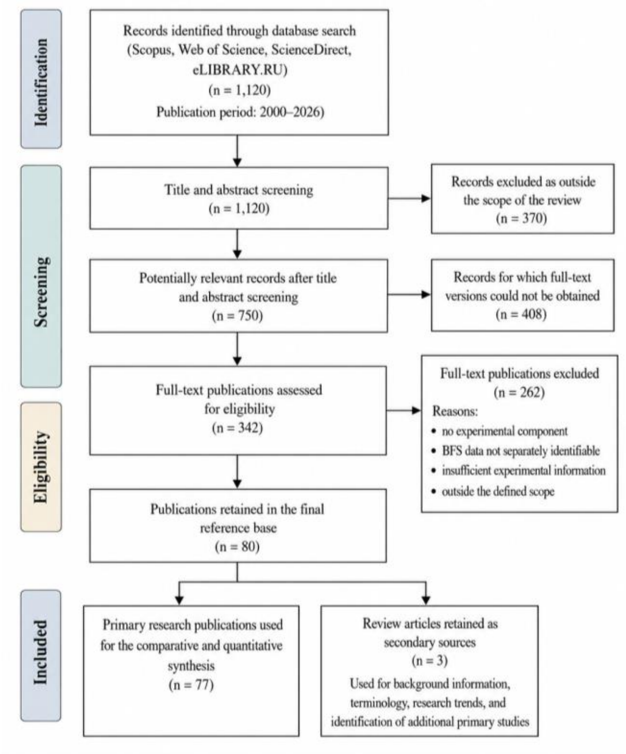

Figure 2 – Flow diagram of the literature search and selection procedure

Primary studies were considered suitable for comparative analysis when they met the following conditions:

- they investigated blast furnace slag or one of its principal forms;

- contained an experimental component;

- examined its use as an aggregate, cementitious component, mineral or reactive filler, pavement-base or subbase material, or soil-stabilization component;

- reported quantitative results allowing the influence of slag incorporation or treatment to be evaluated;

- provided sufficient information on the experimental conditions and composition of the investigated material.

Studies were excluded from comparative analysis when they dealt exclusively with metallurgical slags other than blast furnace slag, did not report the BFS-related results separately, did not contain original experimental data, lacked sufficient information for interpretation of the experimental results, or addressed applications outside the scope of road construction and related construction materials. Duplicate records and repeated publications reporting the same experimental dataset were considered only once.

The methodological suitability of the primary studies was assessed during full-text analysis. Particular attention was given to clear identification of the blast furnace slag type, description of the investigated materials and mixture composition, specification of the slag content or replacement level, description of the experimental procedure, and availability of quantitative performance data. Studies for which these parameters could not be established with sufficient confidence were not used for quantitative comparison.

To ensure a uniform interpretation of the studies reviewed, the following terms and definitions were used. Blast furnace slag (BFS) was used as a general term encompassing various forms of blast furnace slag. Air-cooled blast furnace slag (ACBFS) was defined as a slowly cooled, predominantly crystalline slag mainly used as coarse or fine aggregate. Granulated blast furnace slag (GBFS) was defined as a rapidly cooled, unground slag used as a granular material or fine aggregate. Ground granulated blast furnace slag (GGBFS) was defined as ground GBFS, primarily used as a supplementary cementitious material or as a mineral or reactive filler. The abbreviation GGBFS is used consistently throughout the main text, tables, and figures, whereas the alternative abbreviation GGBS is retained only when reproducing the terminology of the source, including article titles and the corresponding entries in the comparative tables.

Coarse aggregate refers to the larger particle-size fraction, whereas fine aggregate refers to the smaller particle-size fraction. The nominal boundary between these fractions varies among standards; a value of 4 mm is commonly used in European practice, while other national systems use different limits.

The primary studies were compared by slag type, application, mixture composition, replacement approach, test conditions, and reported performance. They were grouped into four application areas:

1) BFS as aggregate in cement concrete;

2) BFS as a supplementary cementitious component;

3) BFS in pavement bases, subbases, and soil stabilization;

4) BFS in asphalt mixtures.

The main experimental conditions and quantitative results for each group were compiled in tables 2-5. Particular attention was given to the slag type, the component being replaced, the replacement or dosage level, the modification or activation method, and the resulting changes in mechanical properties, durability, and other performance characteristics.

Direct comparison of replacement percentages reported in different studies was carried out with caution because the same numerical value may refer to different material functions. ACBFS is generally used as a replacement for natural coarse or fine aggregate, whereas GBFS and GGBFS may be used as granular material, supplementary cementitious components, or mineral and reactive fillers. Accordingly, the interpretation of the reported replacement levels was based on the type of slag, the component being replaced, and the basis on which the dosage was calculated.

Results and Discussion

Table 1 shows the chemical compositions of blast furnace slag given in various scientific studies. As can be seen from Table 1, the chemical composition differs significantly depending on the source of the slag. Nevertheless, CaO, SiO_2, Al_2O_3, and MgO are the principal oxide components in most of the investigated slags. The reported contents are approximately 29–50% CaO, 27–42% SiO_2, 5–22% Al_2O_3, and up to 21% MgO. Together, these oxides generally account for more than 90% of the slag composition [[12], [13], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41], [42], [43]].

Table 1 - Chemical composition of blast furnace slags reported in the reviewed studies, wt.%

Slag	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	MnO	S	SO_3	Na_2O	K_2O	Source
WBFS	32.54	32.53	12.14	1.59	17.60	1.03	1.05		0.12	0.60	Kambole C, et al. [12]
FBFS	35.09	35.51	13.72	1.75	9.16	1.37	0.59		0.30	1.26	
BFS	34-43	27-38	7-12		7-15	0.15-0.76	1.0-1.9				Ren Q, et al. [13]
GGBFS	44.9	35.4	13.0	0.47	5.01			1.31		0.37	Lee G, et al. [16]
GBFS	39.1	35.1	12.8	0.7	10.1			-			Bonavetti VL, et al. [17]
BFS	42.69	40	7.35	2.28	5.19			1.24		0.74	Deboucha W, et al. [18]
ACBFS	30-40	28-42	5-22	0.3-1.7	5-15	0.2-1	1-2				Kanniyappa N, et al. [19]
GBFS	35.7	36.9	9.41	2.28	9.03		1.6	0.06	1.1	1.2	Fuentes-Romero M, et al. [20]
GBFS	37.8	35.11	17.54	-	5.54			0.7	0.38	0.98	Özkan O. [21]
BFS	38.96	35.5	12.52	0.54	9.88			0.54	0.07	0.43	Carrasco MF, et al. [22]
GBFS	38.05	34.87	14.38	0.89	8.03			1.96	<0.01	0.72	Kovtun M, et al. [23]
BFS	40.8	35.4	13	0.5	8.0			0.1	0.2	0.5	Zhou J, et al. [24]
GBFS	37.8	33.4	11.3	0.5	8.9	0.5		3.4	0.5	0.9	Burciaga-Díaz O, et al. [25]
ACBFS	41.37	39.01	9.14		7.57	0.51			0.01	0.64	Nicula LM, et al. [26]
GGBFS	40.80	38.10	9.50	0.56	8.10	0.23			0.30	0.68	
BFS	40.47	35.28	9.71	0.56	8.76			3.79	0.41	0.45	Bleszynski R, et al. [27]
BFS	21.98	33.69	8.69	23.73	0.88	2.47		0.949		0.89	Vadhera K, et al. [28]
GGBFS	32.61	36.70	14.21	0.98	10.12			0.99	0.42	0.76	Yahyaee T, Elize HS [29]
ACBFS	31.1	31.3	11.9	1.67	13.7	0.291			0.515	0.639	Tole I, et al. [30]
GGBFS	30.3	34	11.6	0.291	12.1	0.516			0.531	0.811	
BFS	39.63	38.3	8.81	0.98	5.54			1.35	0.13	0.59	Benmammar M, et al. [31]
GBFS	37.79	35.09	17.54		5.50	0.83	0.66		0.30		Yuksel I, et al. [32]
BFS	32.45	32.47	9.94	1.25	9.31	3.51	0.33	0.82	0.31	0.85	Geçkil T, et al. [33]
BFS	44.50	33.84	10.35	0.67	7.99			-	0.20	0.40	Lübeck A, et al. [34]
GGBFS	41.81	36.44	11.60	0.78	5.8	0.55			0.345	0.428	Nicula L. M, et al. [35]
BFS	30.4	35	14.3	0.3	16.1	0.5		0.7	0.6	0.7	Humad AM, et al. [36]
GBFS	37.09	35.91	12.56	0.34	11.23			1.19	0.25	0.49	Tan K, et al. [37]
ACBFS	44.3	40.7	8.0		5.2	0.2	0.65				Kunaev V, et al. [38]
GBFS	33.9-40.9	34.3-42.0	9.0-12.9	0.00-1.74	8.7-14.0	0.10-1.11			0.19-0.72	0.19-1.52	Adigamov RR, et al. [39]
GGBFS	37.34	37.73	14.42	1.11	8.71	0.02	0.39				Karikatti V, et al. [40]
GBFS	34.4	42.0	12.2	1	6.8	1.1	0.6			0.9	Soğanci AS, et al. [41]
GGBS	32.61	36.7	14.21	0.98	10.12			0.99	0.42	0.76	Yahyaee T, et al. [42]
BFS	38.10	36.00	13.00	0.60	6.60			0.60	0.50	1.10	Bagheri AR, et al. [43]

The differences between individual samples are most noticeable for MgO and Al_2O_3. CaO and SiO_2 contents are comparatively less variable, although their ratio also changes between slag sources. These variations reflect differences in raw materials, blast-furnace operation, cooling conditions, and subsequent processing. Therefore, slags classified under the same general term may differ substantially in mineral structure and engineering behaviour.

The cooling method is particularly important when the slag is considered for construction applications. Slowly cooled ACBFS is mainly crystalline and commonly has a rough and porous particle surface. These characteristics are relevant when the material is used as aggregate because they affect water absorption, particle strength, compaction, and the quality of the aggregate–paste or aggregate–bitumen interface. Rapidly cooled GBFS contains a larger glassy fraction, while grinding increases its specific surface and produces GGBFS suitable for use as a cementitious component.

The $CaO–SiO_2–Al_2O_3–MgO$ composition of GBFS and GGBFS provides the chemical basis for their latent hydraulic behaviour. During hydration or activation, these materials can contribute to the formation of calcium silicate hydrate and calcium aluminosilicate hydrate phases. However, chemical composition alone is insufficient to predict performance. Fineness, glass content, activation conditions, replacement level, and the composition of the surrounding binder also influence the resulting properties.

Blast furnace slag as aggregate in cement concrete.

Blast furnace slag is used as both coarse and fine aggregate in cement concrete. The studies summarized in Table 2 show that the resulting properties depend not only on the replacement level but also on slag type, particle porosity, grading, mixture composition, and compaction conditions.

Several studies reported favourable results at moderate replacement levels. About 30% ACBFS replacement of natural coarse aggregate gave the best overall result in M25 concrete [19]. For unground GBFS used as fine aggregate, favourable results were reported at about 20–30% replacement [[32], [44]], while 30% replacement of natural river sand with GBFS produced the highest compressive, splitting tensile, and flexural strengths in [45]. In road concrete containing a constant GGBFS dosage and 20–60% ACBFS sand, the mixture with 20% ACBFS showed the lowest pore density after 300 freeze–thaw cycles [35], the highest wear resistance among the slag mixtures [46], and lower shrinkage [47]. These results explain why replacement levels of approximately 20–40% occur repeatedly in the reviewed studies. This range, however, should be regarded only as a recurring tendency and not as a universal optimum.

Table 2 – Blast furnace slag as coarse or fine aggregate in cement concrete for road and civil construction

Authors	Year	Substitution approach	Key quantitative results
Kanniyappan SP, et al. [19]	2018	Replacement of natural coarse aggregate with ACBFS at 0%, 10%, 20%, 30%, 40%, and 50% in M25 concrete.	At 28 days, compressive strength peaked at 35.64 MPa with 30% ACBFS, 19.4% above the control (29.86 MPa). Split tensile strength reached a maximum of 4.99 MPa at 40% ACBFS, 28.6% above the control (3.88 MPa). The authors recommended ACBFS contents up to 30% for overall use.
Özkan Ö [21]	2007	Fly ash replaced part of the cement, while unground CBA and GBFS replaced fine aggregate (FA). Two series were studied: M1 with CBA+GBFS and M2 with FA+CBA+GBFS; properties were measured at 7, 28 and 90 days.	Compressive strength, bulk density and water absorption all decreased as the combined waste content increased. The authors considered the modest strength reduction acceptable only for low-strength concrete when CBA and GBFS contents were kept within reasonable limits.
Nicula LM, et al. [26]	2023	Road-concrete mixes contained 15% GGBS replacing cement and either 25% or 50% ACBFS replacing natural sand; reference mix contained conventional cement and natural aggregate. Mortars with 50% GGBS were also studied for HAI.	Flexural strength increased from 28 to 90 days by 20.72% and 20.26% for the two slag concretes, versus 18.58% for the reference. The 15% GGBS + 25% ACBFS concrete reached performance similar to the control at 90 days. GGBS was strength class 80 at 28 days and class 100 at 90 days by HAI.
Vadhera K, et al. [28]	2017	BFS incorporated into rigid-pavement concrete replacing stone coarse aggregate (0%, 20%, 40%, 60% and 100%)	Concrete with 100% slag aggregate showed 10% higher compressive strength than conventional. Split tensile strength dropped 48% at 40% slag but rose ~10% at higher replacements.
Yahyaee T, et al. [29]	2024	GGBFS replaced 30%, 40%, and 50% of Portland cement by mass; steel or carbon fibers were added at 0.5%, 1.0%, and 1.5% by concrete volume; w/c = 0.40.	At 28 days, G50S1.5 reached 30.1 MPa, only 5.5% below the control. At 90 days, G50S1.5 showed >38% higher compressive strength than the control. G30S1.5 increased flexural strength by 33.3% at 28 days and 32.22% at 90 days. G50S1.5 improved abrasion resistance by 25%, while G50S0.5 reduced CO_2 emissions by 40.34%.
Yuksel I, et al. [32]	2007	Non-ground GBFS, bottom ash (BA), or an equal GBFS+BA blend replaced 10%, 20%, 30%, 40%, and 50% of the natural 0–3 mm fine aggregate. Durability was assessed by high-temperature, freeze–thaw, drying–wetting, capillarity, and abrasion tests.	Freeze–thaw resistance improved at low-to-moderate replacement levels, with the best performance around 20% and an acceptable range of 20–30%. The 10% replacement level gave the lowest capillarity, while all mixtures remained within abrasion limits. Overall, the authors identified 20% fine-aggregate replacement as the optimum level for normal concrete.

Nicula LM, et al. [35]	2021	Three slag road-concrete mixes used a constant 54 kg/m³ GGBS and 20%, 40% or 60% crushed ACBFS aggregate; two conventional concretes used 360 and 414 kg/m³ Portland cement. Samples were subjected to 300 freeze–thaw cycles.	After 300 freeze–thaw cycles, S54/20 (containing 360 kg/m³ (cement) + 54 kg/m³ (GGBS) and 20% (ACBFS)_0/4 mm + 80% (natural sand)_0/4); showed the lowest pore density and the highest compressive strength. Mixtures with 40–60% ACBFS exhibited increased gel and capillary pore sizes.
Adigamov RR, et al. [39]	2020	Milled granulated BFS replaced 40% of Portland cement in road-pavement concrete.	40% GGBFS replacement yielded 6.80 MPa flexural and 53.5 MPa compressive strength, reduced water absorption by 45% (to 2.6%), doubled frost resistance, and improved abrasion resistance by 40%.
Nicula LM, et al. [48]	2020	Three road-concrete mixtures contained a constant 54 kg/m³ GGBFS (13% cement replacement relative to the 414 kg/m³ cement control) and 20%, 40% or 60% crushed ungranulated blast-furnace slag (0/4 mm) replacing natural sand.	After 300 freeze–thaw cycles, S54/20 showed no measurable reduction in freeze–thaw resistance (UPV = 4.642 km/s; dynamic modulus = 41.26 GPa), while the reduction was only 0.12% for S54/40 and 2.74% for S54/60. Water penetration remained below 8 mm for S54/20 and S54/40 but increased to 16 mm for S54/60.
Cao Q, et al. [49]	2022	ACBFS coarse aggregate replaced limestone coarse aggregate by volume at 30%, 50% and 100%; both straight and hooked steel fibres were incorporated in ultra-high-performance fiber-reinforced concrete (UHPFRC) mixtures.	A 30% ACBFS replacement produced mechanical properties close to, and in some cases slightly higher than, those of natural-aggregate UHPFRC. At 100% replacement, compressive strength decreased by about 4.5% in UR100 and 14.4% in UB100; elastic modulus decreased by about 2%, while flexural strength decreased by 9.44% and 30.25%, respectively. Workability and density decreased as ACBFS content increased.
Nicula LM, et al. [47]	2023	Five road-concrete mixtures: controls S360 and S414; slag mixtures contained 360 kg/m³ cement + 54 kg/m³ GGBS and replaced natural 0/4 mm sand with ACBFS at 20%, 40% and 60%.	At 150 days, flexural tensile strength reached 6.57 MPa for S54/20 (mix with 20 % BFS) and 6.31 MPa for S54/60. Shrinkage versus S414 decreased by 32.02% for S54/20 and 27.53% for S54/60 (mix with 60 % BFS). At 480 days, all slag concretes exceeded controls in compressive strength; S54/60 was highest. S54/20 showed the lowest portlandite content and Ca/Si = 1.96.
Verian KP, et al. [50]	2015	Natural dolomite coarse aggregate was replaced with ACBFS. Four pavement concretes were studied: ACBFS - and dolomite-based mixtures with either 100 % ordinary Portland cement (OPC) or 20% Class C fly ash replacing OPC by mass; w/cm = 0.42.	ACBFS concrete developed up to ~6% higher compressive strength but up to ~15% lower flexural strength than dolomite concrete. Under $CaCl_2$ freeze–thaw exposure, plain ACBFS concrete failed after 111 cycles versus 151 cycles for plain dolomite concrete, whereas the corresponding fly-ash concretes remained intact after 321 and 350 cycles, respectively.
Sawant AB, et al. [51]	2019	Natural coarse aggregate was replaced by BFS at 50%, 75% and 100%. Two M40 concrete mixtures with w/c = 0.50 (Mix A) and 0.45 (Mix B) were investigated.	Among the BFS mixtures, 50% coarse-aggregate replacement gave the highest compressive strength. At 28 days, 50% BFS reached 48.15 MPa versus 48.74 MPa for the Mix A control and 48.74 MPa versus 50.52 MPa for the Mix B control. At 56 days, the corresponding BFS concretes exceeded the controls, reaching 50.07 vs. 49.04 MPa and 55.70 vs. 53.93 MPa, respectively.
Ta Y, et al. [52]	2023	Granulated blast-furnace slag fine aggregate replaced silica sand at 25%, 50%, 75% and 100% by volume. Freeze–thaw resistance under 3% NaCl exposure, electrical resistivity, chloride-ion diffusion, and ITZ microstructure were evaluated.	Freeze–thaw resistance improved as the BFS fine-aggregate fraction increased. At w/c = 40%, mortar with BFS-H retained >80% of its mass after 28 cycles, whereas the crushed-sand mortar was nearly destroyed by 24 cycles. Mixtures containing ≥75% BFS-I retained >90% of their mass after 10 cycles, while the silica-sand reference was almost completely deteriorated. BFS also increased electrical resistivity and reduced chloride-ion diffusion. A 0.45–1.4 µm reaction layer containing hydrotalcite-like phases was identified at the BFS–cement-paste ITZ.

Dhanasri K, et al. [53]	2013	Natural coarse aggregate was replaced with BFS and natural fine aggregate with crusher dust simultaneously at 0–100% in 10% increments; concrete proportion 1:1.86:3.77, w/c = 0.45.	At 30% replacement, 28-day compressive strength remained approximately equal to the control, while splitting tensile and flexural strength showed only a marginal increase. Above 30%, the mechanical properties declined.
Ríos JD, et al. [54]	2019	ACBFS used as industrial-waste aggregate in self-compacting concrete; the study compares concrete containing slag aggregate with conventional SCC.	50% ACBFS in self-compacting concrete lowered density (3-5%) and strength (23.7-26.5 MPa vs. 41.2 MPa), but vibrated mixes reached 56.7 MPa - 37% higher than reference overcoming porosity via compaction. Fracture energy rose 10.5-30% (51.3-60.6 N/m), with minor tensile loss. Leaching confirmed ACBFS as inert (EU 2003/33/EC).
Vamsi Mohan U, et al. [44]	2017	Natural fine aggregate and sand were replaced with 10%, 20%, and 30% GBFS.	Concrete with 20% GBFS reached 48.04 MPa at 28 days (w/c=0.3), 14% higher than the reference (42.14 MPa); at 30%, strength fell to 27.81 MPa (34% lower), indicating ~20% as optimal. Gains were strongest at low w/c (0.3-0.4), where GBFS densified the microstructure and enhanced long-term strength.
Džananović A, et al. [55]	2018	The authors used BFS (fraction 0/4mm, 4/8mm, 8/16mm, 16/31,5mm, 8- 11,2 mm, 11,2- 16 mm, 16-22,4mm) in concrete.	100% BFS aggregate concrete reached 39.5 MPa at 28 days, 32% above the C25/30 benchmark.
Nicula LM, et al. [46]	2020	Three slag concretes contained 54 kg/m³ GGBS and replaced natural 0/4 mm sand with ACBFS at 20%, 40% and 60%; compared with conventional S360 and S414 mixtures. Abrasion was tested at 100 and 150 days by the Böhme method.	Wear resistance was highest for the mix with 20 % BFS and lowest for the mix with 60 % BFS. Abrasion resistance followed compressive strength inversely through volume loss: stronger mixtures had lower abrasion loss. 20 % BFS and 40 % BFS exceeded S414, but slag mixtures were below the richer S360 control.
Sawant AB, et al. [56]	2019	Natural coarse aggregate was replaced by BFS at 50%, 75% and 100%. Two M40 concrete mixtures with w/c = 0.50 (Mix A) and 0.45 (Mix B) were investigated.	Among the BFS mixtures, 50% coarse-aggregate replacement gave the highest compressive strength. At 28 days, 50% BFS reached 48.15 MPa versus 48.74 MPa for the Mix A control and 48.74 MPa versus 50.52 MPa for the Mix B control. At 56 days, the corresponding values were 50.07 vs. 49.04 MPa and 55.70 vs. 53.93 MPa, respectively.
Singh G, et al. [57]	2015	GBFS used as replacement for natural sand in concrete; several contents were investigated together with compressive-strength and cost analysis.	Under normal curing, maximum compressive strength occurred at 50% GBFS (35.62 MPa at 28 d and 40.63 MPa at 90 d), compared with 20.79 and 22.56 MPa for the control. Under artificial marine conditions, maximum strength occurred at 60% GBFS (32.63 and 36.58 MPa at 28 and 90 d). Considering both strength and economy, the authors identified 40–50% GBFS as optimum under normal conditions and 50–60% under marine conditions.
Mujedu KA, et al. [58]	2018	100% replacement of crushed granite coarse aggregate by BFS in two nominal mixes, 1:1.5:3 and 1:2:4, both with w/c = 0.55.	Slump decreased from 47–48 to 41–43 mm for the 1:1.5:3 mix and from 45–46 to 39–40 mm for the 1:2:4 mix. At 28 days, compressive strength decreased from 20.00 to 18.96 MPa and from 17.93 to 17.33 MPa, respectively. BFS concrete also had lower density, although all measured densities remained within the normal-concrete range (2200–2550 kg/m³).
Pawar VS, et al. [45]	2022	Natural river sand was replaced with GBFS. Compressive strength was evaluated at replacement levels of 25%, 30%, 35%, 40%, and 50%, while splitting tensile and flexural strengths were evaluated at 25%, 30%, and 35%.	The best overall mechanical performance was reported at 30% replacement. Relative to the control concrete, compressive strength increased by 11.80%, splitting tensile strength by 22.64%, and flexural strength by 12.53%. Strength generally decreased when the GBFS content exceeded 30%.

The effect of slag aggregate also differs between individual performance indicators. In [32], the lowest capillarity was obtained at 10% GBFS, whereas the best freeze–thaw performance occurred at about 20%, with 20–30% considered an acceptable range. All mixtures tested in that study remained within the abrasion limits. In UHPFRC, 30% ACBFS produced mechanical properties close to those of the natural-aggregate reference, while further replacement reduced workability, flexural strength, fracture toughness, and fracture energy [49]. In pavement concrete, ACBFS increased compressive strength by approximately 6% compared with dolomite aggregate, but flexural strength was about 15% lower [50]. These results show that the replacement level associated with the highest compressive strength may not provide the best response for other properties relevant to pavement performance.

Higher replacement levels can nevertheless be effective in some mixtures. Complete replacement of natural aggregate with BFS gave higher compressive strength than conventional concrete in [28] and [55]. In contrast, self-compacting concrete containing ACBFS aggregate showed compressive strengths of 23.7–26.5 MPa compared with 41.2 MPa for the reference mixture, while vibration increased the strength to 56.7 MPa [54]. This difference indicates that the performance of high slag contents is strongly affected by particle quality and the degree of compaction.

Figure 3 summarizes the BFS replacement levels for which favourable values of selected performance indicators were reported. The ranges represent the span between the lowest and highest reported contents associated with favourable results and should not be interpreted as continuous optimum intervals. Intermediate contents were not necessarily tested in all studies and did not necessarily produce the same level of performance. Isolated favourable values outside the main ranges are shown separately.

Pretreatment can substantially improve the properties of ACBFS aggregate. Density-based separation reduced water absorption from approximately 4.9–6.8% to 2.19–3.13%, decreased the crushing value from 30–31% to 20–21%, and increased frost resistance from about 150 to 300–400 cycles [6]. Selective crushing followed by hydrophobization reduced water absorption to 1.08% and the mass loss after 15 sodium-sulfate cycles to 1.87% [38]. These results indicate that the replacement level should be considered together with the physical quality of the slag fraction. Removal of weak and highly porous particles can reduce variability and allow higher slag contents to be used without the same loss of aggregate quality.

GGBFS as a supplementary cementitious material.

In addition to its aggregate function, blast furnace slag is frequently used as a supplementary cementitious material in various composites (Table 3). In [18], replacement levels up to 30% provided equal or higher medium- and later-age strength, whereas 40% GGBFS reduced capillary absorption by approximately 40%. In [31], contents above 40% produced a marked increase in 28-day porosity. Conversely, long-term testing of pavement concrete showed that slag mixtures could exceed control strength at 480 days [47]. Assessment at only 7 or 28 days therefore systematically underestimates the later-age contribution of GGBFS.

The replacement levels associated with the highest strength and the best durability performance did not necessarily coincide in the studies summarized in Table 3. Several studies reported favourable combinations of early strength, workability, and later-age performance at GGBFS contents within approximately 20–40% of the cementitious component [[18], [31], [39], [59], [60]]. This interval should be regarded as a recurring tendency in the reviewed evidence rather than as a generally applicable optimum. Higher contents of 50–70% may be justified when electrical resistivity, chloride resistance, clinker reduction or specialized performance is prioritized. For example, 50% GGBFS in white cement produced approximately 35–60 MPa compressive strength, about five times the electrical resistivity and 14.6% lower cost, whereas further slag addition increased resistivity but reduced strength [34]. Increasing the GGBFS content from 10% to 50% resulted in a denser pore structure. At 50% replacement, the average pore diameter decreased by 47% at 28 days. The same mixtures also showed lower chloride permeability and higher electrical resistivity in long-term tests, although carbonation became more pronounced at higher GGBFS contents [42].

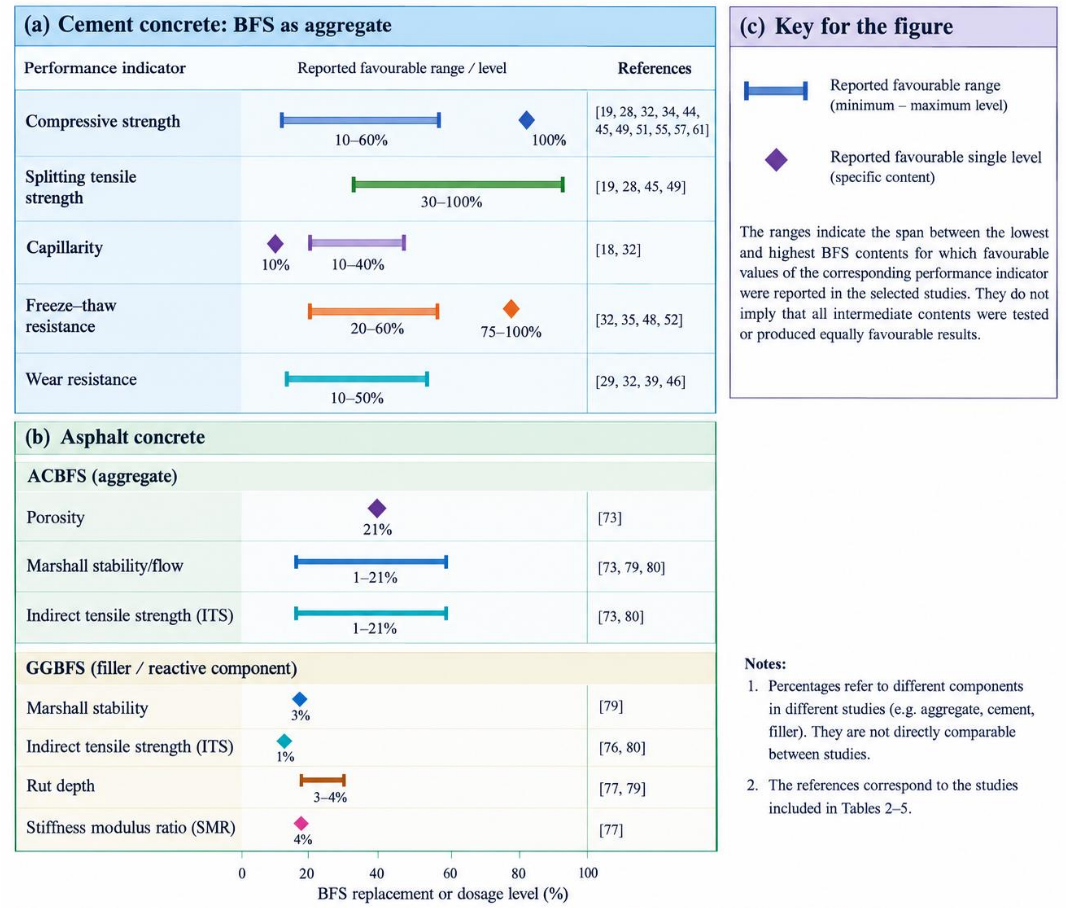

Figure 3 – Reported BFS replacement levels associated with favourable values of selected performance indicators

Table 3 – BFS as a supplementary cementitious material in cement-based composites

Authors	Year	Substitution approach	Key quantitative results
Bonavetti VL [17]	2014	Portland cement was replaced by silica fume up to 10% and/or GBFS up to 70%; binary and ternary binders were studied under sealed curing.	Silica fume provides early-age acceleration, while GBFS contributes to later-age strength; their synergy enables high clinker replacement without proportionate strength loss.
Deboucha W, et al. [18]	2015	Cement replaced separately with BFS or natural pozzolana at 10%, 20%, 30% and 40%.	BFS replacement up to 30% produced equal or better medium- and long-term strength than the control. At 40% BFS, capillary water absorption decreased by approximately 40% relative to the control; the control absorption was about 3.32 kg/m².
Fuentes-Romero M, et al. [20]	2011	100% H-class cement; 100% GBFS activated with 2% or 5% NaOH; and H-class cement/GBFS blends containing 20%, 40%, 60% and 80% GBFS. Sulfate resistance and alkali-aggregate reactivity were evaluated.	Pure H-class cement exceeded 20 MPa by 7 days; the 20% GBFS blend exceeded 20 MPa by 14 days. Increasing NaOH from 2% to 5% increased activated-slag strength. However, slag addition reduced early strength and the authors concluded that overall durability was limited for the tested composites.
Carrasco MF, et al. [22]	2005	Portland cement was replaced by combined limestone filler and BFS, with the experimental domain including up to 22% limestone filler and varying BFS content; strengths were measured at 2, 7, 14, 28, 90 and 360 days.	The ternary LF–BFS–PC blend outperformed the individual binary systems because limestone filler improved early strength and BFS improved later strength. Quadratic strength models had R^2 values of at least 0.80.

Zhou J, et al. [24]	2009	ECC matrices contained Portland cement, limestone powder and BFS; BFS replacement of cement increased from 50% to 70%. A simplified mixture used CEM III/B slag cement and limestone powder. PVA fibre content was 2% by volume.	At 28 days, the optimized mixture achieved 3.3% tensile strain capacity, 57 µm crack width and 38 MPa compressive strength. The simplified CEM III/B mixture achieved 3.1%, 76 µm and 40 MPa, respectively. All mixtures had average crack widths below 100 µm.
Bleszynski R, et al. [27]	2002	Seven field and laboratory concretes, including three ternary Portland cement–silica fume–blast-furnace slag mixtures.	After approximately 2 years of outdoor exposure, significant alkali–silica expansion occurred in the high-alkali control, whereas it was not observed in the ternary mixtures. Ternary systems also showed improved resistance to chloride ingress and deicer-salt deterioration.
Benmammar M, et al. [31]	2019	Reference concrete plus silica-fume concretes at 5%, 10% and 15% cement replacement and BFS concretes at 20%, 40% and 60%; binder = 350 kg/m³ and w/p = 0.50.	At 28 days, ultrasonic pulse velocity of all mixtures was approximately 3.96–4.36 km/s. Silica-fume concretes had higher dynamic modulus, UPV and compressive strength than the control. BFS slowed early hydration; porosity increased markedly above 40% replacement.
Lübeck A, et al. [34]	2012	White Portland cement replaced with 50% or 70% GGBFS; corresponding grey-cement mixtures and 100% white/grey cement controls were tested at several w/b ratios. Some mixtures used Na2SO4 activation.	The 50% GGBFS + 50% white-cement concrete delivered approximately 35–60 MPa compressive strength, about five times the electrical resistivity of the reference, 14.6% lower cost per m³, and nearly unchanged whiteness. Higher slag contents increased resistivity but reduced strength.
Divsholi BS, et al. [42]	2024	Portland cement replaced with 10, 30 and 50% GGBFS; w/cm = 0.4, 0.5 and 0.6	Increasing GGBFS content refined the pore structure; at 50% replacement the average pore diameter decreased by 47% at 28 d. At 4 years, chloride permeability remained very low (~400–800 C, depending on w/cm), while electrical resistivity reached 33–72 kΩ·cm. Compressive strength was maintained or slightly increased, although carbonation increased at 30–50% replacement.
Bagheri AR, et al. [43]	2012	Binary slag concretes contained 15%, 30% and 50% low-reactivity Grade 80 slag; binary silica-fume concretes contained 2.5%, 5%, 7.5% and 10% SF; ternary combinations were also tested. Total binder = 420 kg/m³ and w/b = 0.38.	Silica fume only moderately accelerated strength development of low-reactivity slag concrete but substantially improved electrical resistance, RCPT and chloride-migration performance up to 180 days. Ternary blends also required less superplasticizer than silica-fume-only mixes.
Familusi AO, et al. [59]	2017	A partial replacement of cement in concrete with 0%, 5%, 10%, 15%, and 20% BFS.	20% BFS replacement gave peak 28-day strength (20.87 N/mm²), 67% above control (12.50 N/mm²; F=5.873, $p<0.01$), despite lower workability at w/c=0.5.
Verma N, et al. [61]	2016	Replacement of fine and coarse aggregate of cement with 10%, 20%, 30% BFS and sand with Cast Iron Chips	Replacing cement with 10-20% BFS (with 30% cast iron chips) slightly increased compressive strength, but at 30% BFS + 30% chips, strength dropped by 6.12% (7 days) and 1.4% (28 days).
Okba SH, et al. [62]	2006	Addition of 0%, 17,5%, 23,3%, 25%, 35%, 75% BFS into concrete (instead of cement)	Higher slag replacement reduced 28-day strength but increased it significantly by 360 days. Slag mixes showed markedly improved corrosion and sulfate resistance at late ages, with resistance rising as slag content increased. Strength loss was greater in 5% MgSO4 than 2% MgSO4 solutions.
Iravani A, et al. [63]	2022	The study evaluated the effect of ground granulated blast furnace slag on the thermal performance of concrete under repeated heating–cooling cycles.	BFS cement (CEMIII/A) can significantly improve the residual compressive and flexural strengths, particularly after exposure to 20 thermal cycles and in combination with thermally stable aggregates such as basalt.

Babu KG, et al. [60]	2000	Addition of GGBS in concrete at the replacement levels: 0%, 10%, 30%, 50%, 60%, 65%, 70%, 80%	GGBS concrete strength depends on replacement level and age: 10-30% replacement yields 28-day strength comparable to or exceeding control, while 50-80% causes significant reduction. To match conventional concrete strength at 50% and 65% GGBS replacement, binder content must increase by 8.5% and 19.5%, respectively.
Huang H, et al. [64]	2014	BFS in cement paste containing 66% of slag and saturated Ca (OH)2 solution as an activator	66% BFS cement paste achieved ~60% filling of 10 µm cracks after 240 h self-healing in Ca(OH)2 solution. Crack ettringite (9.5 wt.%) doubled bulk content (5 wt.%); carbonation initially raised filling to 56% but declined to 47% upon completion.
De Matos PR, et al. [65]	2020	Pastes and self-compacting concrete (SCC) with GBFS, ACS and LF	ACS as SCM raised paste yield stress by 44-88% and viscosity vs. limestone, needing 0.95-1.36 kg/m³ superplasticizer for target flow. Despite no pozzolanic activity up to 91 days, ACS matched limestone in strength (~50 MPa) and hydration heat (~440 J/g), especially in 50/50 blends.

The efficiency of high replacement levels increases in multicomponent systems. Silica fume accelerates early hydration and compensates for the delayed strength development of GGBFS, while slag provides later-age strength and structural densification [17]. Limestone filler has a similar kinetic role: it improves early strength, whereas GGBFS improves later strength, allowing ternary systems to outperform corresponding binary mixtures [22]. Field exposure of Portland cement–slag–silica fume concretes showed no significant alkali–silica expansion and improved resistance to chloride ingress and deicer salts relative to the high-alkali control [27]. The optimum slag content should therefore not be selected in isolation; it depends on slag reactivity, fineness, activating components, and the target age.

Specialized composites permit even higher GGBFS contents. Engineered cementitious composites containing 50–70% slag replacement achieved 3.3% tensile strain capacity, a mean crack width of 57 µm, and 38 MPa compressive strength [24]. In alkali-activated systems, 100% GGBFS with 5% Na_2O reached up to 120 MPa [25], while chemical acceleration of carbonate-activated slag yielded up to 15 MPa after 24 h, compared with about 2.5 MPa after 48 h without an accelerator [23]. These values cannot be transferred directly to conventional Portland-cement concrete because high alkali concentrations, shrinkage, carbonation, efflorescence, activator safety, and the environmental burden of sodium silicate require separate assessment.

Thus, maximizing the benefits of GGBFS requires an integrated optimization of replacement level, binder composition, and intended service performance rather than pursuing compressive strength alone.

Road bases, subbases and soil stabilization.

In pavement base and subbase layers, the performance of ACBFS is determined mainly by its bearing capacity, resistance to crushing and abrasion, volumetric stability, and behaviour in the presence of water. The studies summarized in Table 4 show that blast furnace slag can provide high bearing capacity, although this result alone is insufficient for assessing its suitability for road-base applications. Fresh and weathered BFS in [12] showed CBR values of 128% and 153%, respectively, with long-term expansion of 0.39% and 0.32%. In [66], CBR values of 95.3%, 88.7%, and 76.1% were obtained for base, subbase, and subgrade conditions, respectively, while the Los Angeles loss reached 49.2%, exceeding the specified 35% limit. These results show that high CBR values may coexist with insufficient resistance to aggregate degradation.

The physical quality of the slag aggregate is therefore an important factor in base and subbase applications. In [6] and [38], selective crushing, density or friction separation, and hydrophobization reduced water absorption, crushing value, and cyclic mass loss. Such treatment can remove weak and highly porous particles and improve the uniformity of the resulting aggregate. For practical use, the assessment of ACBFS should therefore include not only volumetric stability and chemical safety, but also particle density, open porosity, crushing resistance, abrasion resistance, and consistency between batches.

A different relationship applies to bound soil and base stabilization. Adding 20% BFS to clay increased CBR from 25.6% to 222.9%, reduced calculated pavement thickness from 66 to 51 cm, and lowered estimated cost by 5.65% [33]. In a slag–gypsum–reclaimed-asphalt cement-free binder, mixtures with 47.5% GGBFS achieved about 27–29 MPa at 28 days, while 60% GGBFS reached approximately 41

MPa at 90 days [67]. A ternary binder containing 50% GGBFS, 30% electrolytic manganese residue, and 20% cement, used at 5% of dry sediment mass, exceeded 6 and 8 MPa at 7 and 28 days; relative to 8% cement, cement use fell by 87.5%, CO_2 emissions by 84.5%, and cost by 67% [68]. Road bases are therefore among the most promising applications for deep decarbonization because the required strength can be achieved with substantially less clinker than in structural concrete.

Nevertheless, most studies in Table 4 are based on laboratory CBR, UCS, or individual material properties. Reliable service-life prediction requires repeated-load testing, resilient modulus and permanent-deformation measurements, saturation, freeze–thaw cycles, seasonal moisture variation, and long-term leaching. Chemically bound stabilization using GGBFS must also be distinguished from the mechanical action of ACBFS, since identical CBR values may be associated with different failure mechanisms and moisture sensitivities.

BFS in asphalt concrete mixtures.

In recent years, the use of blast furnace slag in asphalt mixtures has attracted increasing attention as a promising approach to improving pavement performance while reducing the consumption of natural aggregates.

Table 5 and Figure 3 confirm the applicability of both ACBFS and GGBFS in asphalt, although the evidence base is smaller than for cementitious composites.

Table 4 – Blast furnace slag for road bases, subbases and soil stabilization

Authors	Year	Substitution approach	Key quantitative results
Kunaev V, et al. [6]	2023	ACBFS aggregate, fraction 20–40 mm; enrichment by grain density. The study compares progressively denser/less porous grain groups.	Water absorption decreased from 4.9–6.8% to 2.19–3.13%; resistance without significant destruction increased from about 150 to 300–400 freeze–thaw cycles; crushing value decreased from 30–31% to 20–21%.
Kambole C, et al. [12]	2019	Weathered blast-furnace slag (WBFS) and freshly produced blast-furnace slag (FBFS) used directly as granular road-base/subbase aggregates.	Soaked CBR: 153% for WBFS and 128% for FBFS. Long-term expansion: 0.32% and 0.39%, respectively. Aggregate crushing, 10% fines, flakiness, plasticity, and compaction complied with South African base/subbase specifications.
Geçkil T, et al. [33]	2020	Clay soil was stabilized with 5%, 10%, 15% and 20% BFS by dry mass of soil; NaOH solution was used to promote the pozzolanic reaction.	At 20% BFS, CBR increased from 25.6% to 222.9% (about 8.71 times). Calculated pavement thickness decreased from 66 to 51 cm (−22.7%; the paper/table reports approximately 29.4% reduction depending on calculation basis), and estimated cost decreased by 5.65%.
Kunaev V, et al. [38]	2024	Selection of the strongest 75% of ACBFS grains by friction enrichment or selective crushing, followed by hydrophobization.	Friction enrichment: water absorption 4.45→3.64%, freeze–thaw mass loss 5.05→2.82%, ACV 30.71→23.80%. Selective crushing: water absorption 4.45→3.15%. Subsequent hydrophobization reduced absorption to 1.34% after friction enrichment and 1.08% after selective crushing. Selective crushing + hydrophobization reduced mass loss after 15 sodium-sulfate cycles to 1.87%.
Soğanci AS, et al. [41]	2023	Low- (CL) and high-plasticity (CH) clay soils were stabilized separately with 5%, 10%, 15% and 20% GBFS by dry mass of soil.	The optimum GBFS content was 10% for CL soil and 15% for CH soil. At 28 days, the unconfined compressive strength increased by 73% (255→442 kPa) for CL soil and by 127% (227.4→508 kPa) for CH soil. At 20% GBFS, the maximum dry density increased by 5.4% for CL and 13.1% for CH soil, while the optimum moisture content decreased by 6.5% and 18.1%, respectively.
Kamara KB, et al. [67]	2021	Portland cement was fully replaced by ternary binders containing GGBS, reclaimed asphalt filler (RAF), and either plasterboard waste gypsum (PWG) or vitamin B5 gypsum (V-B5G). Selected mixtures contained 47.5% or 60% GGBS.	At 28 days, mixtures containing 47.5% GGBS reached 27.02 MPa with PWG and 29.45 MPa with V-B5G. At 90 days, mixtures containing 60% GGBS reached 41 MPa and 40 MPa, respectively.

Hsiung BCB, et al. [69]	2025	ACBFS was used directly as a 30-cm subgrade layer beneath embedded tram track slabs. Its performance was compared with two alternative ground-improvement systems: QS1 + QS2 and QS2 + cement–soil mixture (CSM).	An elastic modulus of 400 MPa was adopted for ACBFS, and a 30-cm layer was selected for the tramway model. The calculated maximum settlement was 3.7 mm with ACBFS, compared with 4.0 mm for QS1 + QS2 and 3.4 mm for QS2 + CSM. For a 6 × 100 m area, the ACBFS layer required 180 m^3 of material, whereas the QS2 + CSM alternative required 300 m^3 of QS2 and 1,800 m^3 of CSM.
Rondón H, et al. [66]	2018	ACBFS was characterized as coarse aggregate for base, subbase, and subgrade applications.	CBR values were reported as 95.3% for base conditions, 88.7% for subbase, and 76.1% for subgrade. Micro-Deval loss: 29.2%; 10% fines value: 123 kN; Los Angeles abrasion/degradation: 49.2%, exceeding a 35% limit. Mineralogy included about 58.9% quartz and 18.1% cristobalite.
Bulko R, et al. [70]	2023	BFS from the Kremnica region tested as a geotechnical bulk material; multiple particle-size fractions and states were characterized.	BFS exhibited CBR values of 31.8–42.8%, an internal friction angle of 38.9–43.0°, and an oedometer modulus of 13.8–24.8 MPa, demonstrating its suitability as a substitute for conventional aggregates in road and earthwork construction.
Kadyrov A, et al. [71]	2019	The study developed a hydrophobized blast furnace slag aggregate for pavement subbase layers, replacing conventional natural crushed stone. The optimized composition consisted of 89.6 wt.% blast furnace slag, 3.7 wt.% microsilica, 6.3 wt.% cement, and 0.4 wt.% used engine oil as a hydrophobic modifier	Compared with untreated slag aggregate, the modified material showed a reduction in water absorption (5.22% to 1,29%), a decrease in ACV (30.23 % to 25.02 %), and a 2.1-fold increase in frost resistance, demonstrating its suitability for road pavement subbase applications
Lang L, et al. [68]	2025	Ternary GEC binder: 50% GGBFS, 30% electrolytic manganese residue, and 20% cement. The optimized binder was used at 5% dry sediment waste and compared with 8% cement.	Reported 7- and 28-day unconfined compressive strengths exceeded 6 MPa and 8 MPa, respectively. Using 5% GEC instead of 8% cement reduced total binder dosage by 37.5%, cement use by 87.5%, CO_2 emissions by 84.5%, and cost by 67%, while improving water and sulfate resistance.
Al-Chaar G, et al. [72]	2019	The study evaluated the use of ground granulated blast furnace slag (GGBFS) as a 30–50 wt.% replacement for Portland cement in concrete intended for rigid pavement and structural applications, comparing its performance with conventional Portland cement concrete.	Concrete containing 30–50 wt.% GGBFS achieved compressive and flexural strengths comparable to or higher than those of the control mix while maintaining satisfactory density and porosity, confirming its suitability for rigid pavement concrete.

Table 5 – Applications of blast furnace slag in asphalt mixtures

Authors	Year	Substitution approach	Key quantitative results
Rondón-Quintana HA, et al. [73]	2019	Replacement of the coarse natural limestone aggregate with treated blast furnace slag (BFS); mixtures incorporating BFS pre-coated with Portland cement paste (BFS-C) were investigated.	PC-treated BFS (BFS-C) at 21% replacement reduced porosity, increased stability/flow by 35%, ITS (dry/wet) by 26.5%/34.4%, and TSR to 90.7%. It showed 6-72% higher resilient modulus and better abrasion resistance, overcoming slag's porosity limitations.
Rondón HA, et al. [74]	2018	21% replacement of the coarse natural aggregate (in WMA) with blast furnace slag (BFS).	At 21% BFS replacement, a significant increase in stiffness and moisture damage resistance was achieved, while the abrasion resistance remained comparable to the control mixture.
Kunaev V, et al. [75]	2025	Selective crushing of air-cooled blast furnace slag (ACBFS) in a ball mill for 30–40 min using a grinding media composition of 50% steel balls and 50% cylpebs.	Bulk density: 1169 → 1396 kg/m^3 (+19.4%); water absorption: 4.96 → 2.38% (−52.0%); aggregate crushing value (ACV): 30.98 → 18.40% (−40.6%); sulfate soundness loss: 5.48 → 1.23% (−77.6%); surface pore content: 45.06 → 15.68% (−65.2%).

Al-Hdabi A, et al. [76]	2019	The study investigated ground granulated blast furnace slag (GGBFS) as a complete replacement for ordinary Portland cement (OPC) mineral filler in hot mix asphalt (HMA). Asphalt mixtures containing GGBFS filler (GGBFSAC) were compared with conventional mixtures containing OPC filler (OPCAC) using Marshall stability, indirect tensile strength, moisture susceptibility, and long-term aging tests.	Marshall stability was 12.09 kN for the GGBFS-filled mixture and 8.62 kN for the OPC-filled control. ITS increased from 1153.93 to 1286.35 kPa, while the index of retained strength increased from 73.5% to 88.5%. Marshall stiffness was 3.11 kN/mm with GGBFS compared with 2.28 kN/mm for the control.
Dulaimi A, et al. [77]	2023	Cold asphalt emulsion mixture containing 4% GGBFS and 2% calcium carbide residue (CCR); 3% pre-wetting water was replaced with waste alkaline $Ca(OH)_2$ solution to produce geopolymer-based cold asphalt emulsion mixture (GCAE).	GCAE: ITSM = 2465 MPa after 3 days; rut depth = 1.7 mm after 10,000 cycles; fracture toughness = 7985 $N/mm^{2/3}$; SMR = 103%. Corresponding traditional limestone filler values were 188 MPa, about 9 mm, 7325 $N/mm^{2/3}$, and 75%.
Del-Valle-Corte J, et al. [78]	2024	The study evaluated ground granulated blast furnace slag (GGBFS) as a partial replacement for virgin mineral filler in warm mix asphalt. Replacement levels of 75% and 100% were investigated, and the optimum mixture containing 75% GGBFS was selected for further mechanical evaluation.	GGBFS-2 mix (75 % GGBFS) exhibited the best fatigue performance but the highest axial deformation and rut depth.
Chegenizadeh A, et al. [79]	2022	Ground-granulated blast-furnace slag (GGBFS) was investigated as a replacement for the conventional 1.5% hydrated lime (HL) filler in dense-graded hot mix asphalt. Four mixtures were evaluated: a control mixture containing 1.5% HL and three mixtures containing 1.5%, 3%, and 5% GGBFS as the sole filler.	The mixture containing 3% GGBFS demonstrated the best overall performance, with Marshall stability of 19.16 kN (an 18.56% increase over the control), fatigue life of 92,524 cycles (a 26% increase), and rut depth of 2.70 mm, representing a 27% reduction compared with the control mixture (3.73 mm). Increasing the GGBFS content to 5% reduced performance, with fatigue life decreasing by 14.68% and rut depth increasing by 16% compared with the 3% GGBFS mixture.
Lu D, et al. [80]	2021	This study developed a cold mix asphalt (CMA) incorporating ground-granulated blast furnace slag (GGBS) as part of a ternary blended cementitious filler replacing conventional limestone filler. The optimum mixture (CMA-B) contained 2% ordinary Portland cement (OPC), 1% fly ash (FA), 1% GGBS, and 2% limestone filler, while the total filler content remained 6% by weight of aggregate.	The optimum mixture containing 2% OPC + 1% FA + 1% GGBS exhibited approximately 20% higher indirect tensile strength, 55% lower raveling loss, residual Marshall stability of about 95%, and dynamic stability approximately 10 times higher than the mixture containing 2% OPC only. T

ACBFS mainly replaces coarse mineral aggregate, whereas GGBFS acts as a mineral or reactive filler. Replacement percentages from different studies must therefore not be compared directly. A 21% BFS content in the coarse fraction of warm-mix asphalt increased stiffness and moisture resistance while maintaining abrasion resistance at the control level [74]. Coating porous BFS with cement paste mitigated water-absorption effects: BFS-C increased the stability/flow ratio by 35%, dry and wet ITS by 26.5% and 34.4%, TSR to 90.7%, and resilient modulus by 6–72% [73]. Surface condition, rather than slag content alone, is therefore a decisive parameter.

Results for GGBFS filler also indicate a distinct optimum. When 1.5% hydrated lime was replaced with 1.5%, 3%, and 5% GGBFS, the best performance occurred at 3%: Marshall stability reached 19.16 kN (+18.56%), fatigue life 92,524 cycles (+26%), and rut depth decreased from 3.73 to 2.70 mm (−27%) [79]. Increasing GGBFS to 5% reduced fatigue and rutting performance relative to the 3% mixture, probably because of excess fines and a changed bitumen–filler volumetric ratio. Conversely, complete replacement of Portland-cement filler with GGBFS increased Marshall stability from 8.62 to 12.09 kN, ITS from 1153.93 to 1286.35 kPa, and retained strength from 73.5% to 88.5% [76]. “100% filler replacement" is not equivalent to "5% of aggregate mass"; the absolute fine content and its role in the mixture are different.

The strongest effects were obtained in cold mixtures, where GGBFS contributes to an inorganic binder rather than acting solely as an inert powder. A mixture containing 4% GGBFS, 2% calcium carbide residue and alkaline $Ca(OH)_2$ solution reached an ITSM of 2465 MPa after three days, approximately 13 times the control; rut depth after 10,000 cycles decreased from about 9.0 to 1.7 mm, and the stiffness modulus ratio increased from 75% to 103% [77]. In another cold mixture, 2% Portland cement, 1% fly ash and 1% GGBFS produced about 20% higher ITS, 55% lower raveling loss and nearly ten times higher dynamic stability than the mixture with 2% cement alone [80]. Weak-alkali activation of GGBFS within asphalt is therefore promising, but long-term ageing, low-temperature cracking, and compatibility with different emulsions and binders must be verified.

Open porosity remains the principal limitation of ACBFS in asphalt. Selective crushing for 30–40 min increased bulk density from 1169 to 1396 kg/m³, reduced water absorption from 4.96% to 2.38%, crushing value from 30.98% to 18.40%, sulfate soundness loss from 5.48% to 1.23%, and surface pore content from 45.06% to 15.68% [75]. These values refer to the aggregate rather than the finished mixture. The next step is to determine whether improved grain quality produces proportional gains in TSR, fatigue life, rutting resistance, and ageing performance.

Future Research Perspectives.

This review presents the results reported in 80 selected scientific articles focusing on the use of blast furnace slag as a binding component and as an aggregate of various size fractions in cement concrete, road bases, soil stabilization, and road asphalt concrete. It has been established that blast furnace slag cannot be considered a uniform and interchangeable secondary raw material. The function performed by blast furnace slag as part of cement concrete, asphalt concrete, or road base depends on its cooling method, phase composition, particle-size fraction, water absorption, aggregate crushing value, bulk density, other physical and mechanical characteristics, as well as pre-treatment. ACBFS, GBFS, and GGBFS perform completely different functions when used in construction. ACBFS is primarily used as coarse or fine aggregate, GBFS as a granular material or fine aggregate, and GGBFS as a supplementary cementitious component or as a mineral and reactive filler.

Differences in the method of cooling and solidification of liquid blast furnace slag, its phase composition, bulk density and particle density, porosity, water absorption, and surface condition make it difficult to compare the results obtained by different researchers and, at the same time, to some extent explain their significant differences. Based on this, the authors of this review consider it necessary, in future studies, to go beyond optimizing the proportion of blast furnace slag in cement concrete or asphalt concrete and to pay more attention to the quality, chemical composition, and variability of the physical and mechanical characteristics of the blast furnace slag itself.

Possible ways to improve the physical and mechanical properties of ACBFS may include hydrophobization (to reduce its water absorption and improve frost resistance) and selective crushing, which makes it possible to remove weak, high-porosity grains while preserving the integrity of stronger grains (to potentially increase the strength of the final product). Studies in these areas are included in this literature review. However, the effects of hydrophobization and selective crushing have been evaluated exclusively at the aggregate level. Future studies should answer the question of whether these additional treatment methods provide a consistent improvement in the physical and mechanical properties and durability of cement concrete, asphalt concrete, and road base materials made using ACBFS of various origins (from different metallurgical enterprises).

Another gap in research identified based on the analysis of the literature is related to the interaction of untreated or pre-treated ACBFS with various binders, including cementitious and bituminous binders. The available data indicate that the surface characteristics of slag can affect interfacial adhesion, moisture resistance, and the performance characteristics of the mixture. Thus, the combined use of ACBFS that has undergone preliminary selective crushing and modified binders, including, for example, bituminous binder containing microsilica or other industrial by-products, may affect the performance characteristics of the finished product (asphalt concrete or cement concrete). Nevertheless, the reviewed literature does not contain sufficient evidence to establish a general synergistic effect, and this concept should be considered a hypothesis requiring experimental verification rather than an established conclusion.

Conclusion

The cooling method largely determines how blast furnace slag is used. Air-cooled slag is mainly crystalline and often has a rough, porous surface, so it is used primarily as aggregate in concrete, asphalt mixtures, and unbound pavement layers. Rapidly quenched slag contains a larger glassy fraction; after grinding, it becomes GGBFS and can be used as a partial Portland cement replacement, a cementitious component in stabilized bases, or a mineral or reactive filler in asphalt.

In cement concrete, many studies reported good results (increased compressive strength and other properties) at ACBFS replacement levels of about 20–40%. This range is not a universal optimum. The outcome changed with slag origin, particle porosity and density, concrete composition, compaction, curing, and the property being measured.

For pavement bases and soil stabilization, BFS often gave high CBR values. Fresh and weathered slag reached 128% and 153%, and adding 20% BFS to clay increased CBR from 25.6% to 222.9%. GGBFS-containing binders also reduced cement use, CO_2 emissions, and cost. At the same time, CBR alone is not enough to judge long-term suitability; abrasion, deformation, moisture, freeze–thaw action, and leaching also matter. Both ACBFS and GGBFS can improve asphalt performance, but through different mechanisms. Treated BFS aggregate at 21% increased the stability/flow ratio by 35%, dry and wet ITS by 26.5% and 34.4%, raised TSR to 90.7%, and increased resilient modulus by 6–72%. For GGBFS used as filler, 3% provided the best overall balance in one study, increasing Marshall stability by 18.56% and fatigue life by 26% while reducing rut depth by 27%. In activated cold mixtures, 4% GGBFS contributed to an approximately 13-fold increase in early ITSM and a reduction in rut depth from about 9.0 to 1.7 mm.

No universal optimum BFS content can be established. Reported dosages refer variously to cement mass, total binder, coarse or fine aggregate, mineral filler, or total aggregate. The optimum consequently depends on slag form, particle quality, processing method, replaced component, mixture technology, curing or ageing conditions, and targeted performance.

The most effective development pathway is an integrated one in which the quality and surface properties of the slag aggregate are engineered together with the cementitious or bituminous binder. The integrated valorization of metallurgical slag and silica-rich industrial by-products can provide a scientifically grounded route to durable pavement materials while reducing both the disposal of industrial residues and the consumption of virgin mineral resources.

Conflicts of interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Жол құрылысында табиғи минералдық материалдарға балама ретіндегі домна қожы: шолу

[1]Кунаев В.А., [1]Ахметова Г.Е., [1]Оспанова А.З., [1]Кенжалиев О.Б., [1]Тавшанов И.С., [2]Fathi M.S., [1]Ульева Г.А., [1]Батырбек Ә.Е., [1]Чарный Д.Ю.

[1]Қарағанды индустриялық университеті КЕАҚ, Теміртау, Қазақстан
[2]Малайзия технологиялық университеті, Куала-Лумпур, Малайзия

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ТҮЙІНДЕМЕ
Ұсынылған әдеби шолу 2000–2026 жылдар аралығындағы ғылыми мақалалардың талдау нәтижелерін қамтиды, онда домендік қожды жол құрылысының әртүрлі бағыттарында қолдану қарастырылады. Домна қожының әртүрлі түрлерін қолдану нұсқалары арасында айқын айырмашылықтардың бар екені анықталды. Үйінді домна қожы көбінесе цементбетон мен асфальтбетон үшін ірі немесе ұсақ толтырғыш ретінде қолданылады, ал ұнтақталған түйіршіктелген домна қожы қосымша байланыстырушы компонент ретінде немесе минералдық/реакциялық белсенді толтырғыш ретінде қолданылады. Домна қожын бетон өндірісінде қолданған кезде бірқатар зерттеулерде ең жоғары нәтижелер толтырғыштың 20-40%- аралығында қожбен алмастыру кезінде алынған, дегенмен бұл көрсеткіш әмбебап оңтайлы мән болып табылмаған. Кейбір мақалаларда домна қожын автомобиль жолының негізі құрамында пайдалану немесе топырақты тұрақтандыру CBR-дің артуымен байланыстырылғаны көрсетілген. Кейбір авторлар құрамында түйіршіктелген домна қожы бар кешенді байланыстырушы материалдарды қолдану кезінде портландцемент шығынының төмендейтінін атап көрсетеді. Сондай-ақ үйінді және түйіршіктелген домна қожын әртүрлі пропорцияларда енгізу кезінде асфальтбетонның суға төзімділігі, шаршауға төзімділігі, Маршалл бойынша ығысуға тұрақтылығы және із түсуге төзімділігінің жақсаруы туралы деректер келтірілген. Кеуектілігі әртүрлі үйінді домна қожын алдын ала өңдеудің де маңызы зор болды: селективті ұсату және кейінгі бөлшектерді бөлу су сіңіруін, ұсақталу көрсеткішін және әлсіз кеуекті түйірлердің үлесін төмендетті. Негізгі практикалық қорытынды домна қожын біртекті және өзара алмастырылатын материал ретінде қарастыруға болмайтынын көрсетеді. Оны қолдану тәсілі қож түрін, түйірлердің сапасын, алмастырылатын компонентті және жол-құрылыс материалының талап етілетін пайдалану қасиеттерін ескере отырып таңдалуы тиіс. Алдағы зерттеулерде қож толтырғышын алдын ала өңдеу нәтижесінде алынған қасиеттердің жақсаруы цементбетонда, асфальтбетон қоспаларында және жол жамылғысы негіздерінің материалдарында ұзақ мерзімді пайдалану кезінде сақтала ма, соны анықтау қажет.

Түйін сөздер: үйінді домна қожы, ұнтақталған түйіршіктелген домна қожы, табиғи минералдық шикізатты алмастыру, толтырғышты байыту, цементбетон, асфальтбетон, жол төсемі негіздерінің материалдары.

Авторлар туралы ақпарат:

Кунаев Вячеслав Александрович	*PhD, доцент, Ғылым және инновациялар департаментінің директоры, Қарағанды индустриялық университеті КеАҚ, 101400, Республика даңғылы, 30, Теміртау, Қазақстан. E-mail: v.kunayev@tttu.edu.kz; ORCID ID: https://orcid.org/0000-0001-8283-7186*
Ахметова Гульжайнат Есенжоловна	*PhD, доцент, Қарағанды индустриялық университеті КеАҚ, 101400, Республика даңғылы, 30, Теміртау, Қазақстан. E-mail: agulzhajnat@bk.ru; ORCID ID: https://orcid.org/0000-0001-8244-5027*
Оспанова Аяулым Зайнуллаевна	*Докторант, Қарағанды индустриялық университеті КеАҚ, 101400, Республика даңғылы, 30, Теміртау, Қазақстан. E-mail: a.ospanova@tttu.edu.kz; ORCID ID: https://orcid.org/0009-0002-0597-1220*
Кенжалиев Олжас Багдаулетович	*PhD, доцент, Қарағанды индустриялық университеті КеАҚ, 101400, Республика даңғылы, 30, Теміртау, Қазақстан. E-mail: o.kenzhaliyev@tttu.edu.kz; ORCID ID: https://orcid.org/0000-0002-3776-9724*
Тавшанов Ильгар Сулейманович	*Ғылыми қызметкер, Қарағанды индустриялық университеті КеАҚ, 101400, Республика даңғылы, 30, Теміртау, Қазақстан. E-mail: i.tavshanov@tttu.edu.kz; ORCID ID: https://orcid.org/0000-0002-9427-9748*
Fathi Mohamad Syazli	*PhD, қауымдастырылған профессор, Малайзия технологиялық университеті, Сұлтан Яхья Петра көшесі, 54100, Куала-Лумпур, Малайзия. E-mail: syazli@utm.my; ORCID ID: https://orcid.org/0000-0002-0474-6278*
Ульева Гульнара Анатольевна	*PhD, профессор, Қарағанды индустриялық университеті КеАҚ, 101400, Республика даңғылы, 30, Теміртау, Қазақстан. E-mail: g.ulyeva@tttu.edu.kz; ORCID ID: https://orcid.org/0009-0002-7300-1277*
Батырбек Әлібек Есімбекұлы	*Докторант, Қарағанды индустриялық университеті КеАҚ, Республика даңғылы, 30, Теміртау, Қарағанды облысы, Қазақстан. E-mail: a.batyrbek@tttu.edu.kz; ORCID ID: https://orcid.org/0000-0002-3369-6804*
Чарный Дмитрий Юрьевич	*Кіші ғылыми қызметкер, Қарағанды индустриялық университеті КеАҚ, 101400, Республика даңғылы, 30, Теміртау, Қазақстан. E-mail: dmitryi.charnyy@gmail.com; ORCID ID: https://orcid.org/0009-0005-9438-2330*

Доменный шлак как альтернатива природным минеральным материалам в дорожном строительстве: обзор

[1]Кунаев В.А., [1]Ахметова Г.Е., [1]Оспанова А.З., [1]Кенжалиев О.Б., [1]Тавшанов И.С., [2]Fathi M.S., [1]Ульева Г.А., [1]Батырбек Ә.Е., [1]Чарный Д.Ю.

[1]НАО «Карагандинский индустриальный университет», Темиртау, Карагандинская область, Казахстан
[2]Технологический университет Малайзии, Куала-Лумпур, Малайзия

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АННОТАЦИЯ
Представленный литературный обзор содержит результаты анализа научных статей за 2000-2026 годы, рассматриваемых применение доменного шлака в разных направлениях дорожного строительства. Установлено наличие четких различий между вариантами применения разных типов доменного шлака. Отвальный доменный шлак чаще все применяется в качестве крупного или мелкого заполнителя для цементобетона и асфальтобетона, а измельченный гранулированный доменный шлак – в роли дополнительного вяжущего компонента либо как минеральный/реактивный наполнитель. При использовании доменного шлака при производстве бетона наиболее высокие результаты в ряде исследований достигались при замене шлаком в пределах 20-40 % заполнителя, хотя данный показатель и не был универсальным оптимальным значением. В отдельных статьях указывалось на связь использования доменного шлака в составе основания автомобильной дороги либо для стабилизации грунта с повышением CBR. Некоторые авторы указывают на снижение расхода портландцемента при применении комплексных вяжущих, содержащих гранулированный доменный шлак. Также приведены данные об улучшении водостойкости, усталостной стойкости, сдвигоустойчивости по Маршаллу, колейности асфальтобетона при введении отвального и гранулированного доменного шлака в различных пропорциях. Важное значение имела и предварительная обработка разнопористого отвального доменного шлака: избирательное дробление и последующее разделение частиц снижали водопоглощение, показатель дробимости и долю слабых пористых зерен. Основной практический вывод состоит в том, что доменный нельзя рассматривать как однородный взаимозаменяемый материал. Способ его применения должен выбираться с учетом типа шлака, качества зерен, заменяемого компонента и требуемых эксплуатационных свойств дорожно-строительного материала. В дальнейших исследованиях необходимо установить, сохраняются ли улучшения свойств, полученные после предварительной обработки шлакового заполнителя, в цементобетоне, асфальтобетонных смесях и материалах оснований дорожных одежд при длительной эксплуатации.

Ключевые слова: отвальный доменный шлак, молотый гранулированный доменный шлак, замещение природного минерального сырья, обогащение заполнителя, цементобетон, асфальтобетон, материалы оснований дорожных одежд.

Информация об авторах:

Кунаев Вячеслав Александрович	*PhD, доцент, директор департамента науки и инноваций, НАО Карагандинский индустриальный университет, 101400, пр. Республики, 30, Темиртау, Казахстан. E-mail: v.kunayev@tttu.edu.kz; ORCID ID: https://orcid.org/0000-0001-8283-7186*
Ахметова Гульжайнат Есенжоловна	*PhD, доцент, НАО Карагандинский индустриальный университет, 101400, пр. Республики, 30, Темиртау, Казахстан. E-mail: agulzhajnat@bk.ru; ORCID ID: https://orcid.org/0000-0001-8244-5027*
Оспанова Аяулым Зайнуллаевна	*Докторант, НАО Карагандинский индустриальный университет, 101400, пр. Республики, 30, Темиртау, Казахстан. E-mail: a.ospanova@tttu.edu.kz; ORCID ID: https://orcid.org/0009-0002-0597-1220*
Кенжалиев Олжас Багдаулетович	*PhD, доцент, НАО Карагандинский индустриальный университет, 101400, пр. Республики, 30, Темиртау, Казахстан. E-mail: o.kenzhaliyev@tttu.edu.kz; ORCID ID: https://orcid.org/0000-0002-3776-9724*
Тавшанов Ильгар Сулейманович	*Научный сотрудник, НАО Карагандинский индустриальный университет, 101400, пр. Республики, 30, Темиртау, Казахстан. E-mail: i.tavshanov@tttu.edu.kz; ORCID ID: https://orcid.org/0000-0002-9427-9748*
Fathi Mohamad Syazli	*PhD, ассоциированный профессор, Технологический университет Малайзии, ул. Султан Яхья Петра, 54100, Куала-Лумпур, Малайзия. E-mail: syazli@utm.my; ORCID ID: https://orcid.org/0000-0002-0474-6278*
Ульева Гульнара Анатольевна	*PhD, профессор, НАО Карагандинский индустриальный университет, 101400, пр. Республики, 30, Темиртау, Казахстан. E-mail: g.ulyeva@tttu.edu.kz; ORCID ID: https://orcid.org/0009-0002-7300-1277*
Батырбек Әлібек Есімбекұлы	*Докторант, НАО Карагандинский индустриальный университет, 101400, пр. Республики, 30, Темиртау, Казахстан. E-mail: a.batyrbek@tttu.edu.kz; ORCID ID: https://orcid.org/0000-0002-3369-6804*
Чарный Дмитрий Юрьевич	*Младший научный сотрудник, НАО Карагандинский индустриальный университет, 101400, пр. Республики, 30, Темиртау, Казахстан. E-mail: dmitryi.charnyy@gmail.com; ORCID ID: https://orcid.org/0009-0005-9438-2330*

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