Vibration-resistant mixed binders using man-made burnt rocks for transport infrastructure

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Abstract. This study presents the characteristics of man-made wastes, specifically burnt rocks formed by the self-combustion of coal-bearing waste dumps, whose chemical and mineralogical composition depends on the origin of the basin. The aim of this research is to assess the feasibility of using these burnt rocks as components of mixed mineral binders and to evaluate their influence on mechanical and dynamic performance parameters. A comprehensive analysis of their physical, chemical, and structural properties was carried out, demonstrating their compatibility with conventional binder materials. The novelty of this study lies in the first systematic use of locally available burnt rocks (glyage) in vibration-resistant binder compositions for transport infrastructure, expanding the raw material base of construction materials while reducing environmental impact. The developed binders achieved compressive strengths up to 17.6 MPa, sufficient for structural layers of pavement bases and subgrade stabilization. Moreover, these mixed binders can modify the dynamic stiffness and damping behavior of pavement structures under moving vehicle loads, establishing a scientific link between binder composition and vibration control in transport engineering. These results are directly relevant to vibration engineering, as the dynamic stiffness and damping behavior of the developed binders influence vibration propagation and attenuation in transport pavements, ensuring longer service life and reduced noise and deformation under dynamic traffic loads.

Keywords: vibration damping, mixed binders, burnt rocks, transport infrastructure, dynamic stiffness, road foundation, sustainable materials.

1. Introduction

Sustainable development of the construction and transportation sectors requires the rational use of material resources and the integration of locally available man-made products into engineering materials. In the Kyrgyz Republic, a large amount of burnt rocks (locally known as glyage) – wastes from coal mining in regions such as Tashkumyr, Kyzyl-Kiya, Jyrgalan, and Kara-Kiche – remain unutilized at an industrial scale. Utilizing these waste materials as components in mineral binders can simultaneously address material shortages, reduce production costs, and mitigate environmental pollution [1-5].

During the oxidative self-combustion of mine rocks extracted together with coal, burnt rocks are formed in the dumps and waste heaps of mines and open pits [6-9]. These burnt rocks contain less than 5 % residual carbonaceous matter and are characterized by the absence or near absence of a glassy phase. They exhibit high pozzolanic activity because, during firing, kaolinites and hydro-aluminosilicates transform into reactive aluminosilicate phases capable of combining with calcium hydroxide to form stable hydrates. The reactivity of these materials depends on the crystal structure, which generally decreases from kaolinite to hydromicas [10-14].

In recent years, research in transportation and vibration engineering has shown that the dynamic performance of pavement and railway structures is strongly influenced by the stiffness and damping properties of binder and base layers. Substituting a portion of traditional binders with industrial by-products such as burnt rocks and fly ash can alter the dynamic modulus, energy dissipation, and vibration transmissibility of the structure. Therefore, studying the mechanical and dynamic behavior of mixed binders containing burnt rocks is not only relevant for construction materials science but also directly connected to vibration performance and durability in transport infrastructure.

The aim of this research is to investigate the physical, chemical, and structural properties of local burnt rocks and to develop mixed binder compositions based on them, assessing their suitability for use in road and railway foundation layers where vibration damping and stiffness control are critical.

In transport infrastructure, vibrations generated by moving vehicles are transmitted through pavement and subgrade layers. The stiffness and damping characteristics of binder materials play a decisive role in controlling vibration propagation, reducing structural fatigue, and improving riding comfort. Therefore, the use of man-made burnt rocks in mixed binders can offer dual benefits: sustainable material utilization and vibration mitigation in road and railway foundations.

The developed binders are intended for use in road and railway foundations, particularly in the base and subgrade layers where dynamic vehicle loads cause vibration, settlement, and fatigue cracking. Their high stiffness and damping capacity make them suitable for vibration-resistant pavement structures, embankments, and foundation blocks in transport infrastructure.

2. Materials and method

The chemical composition of all materials was determined using a Shimadzu XRF-1800 spectrometer. Grinding was performed with a Retsch PM 100 planetary ball mill to achieve a uniform particle size. Material density was measured using a Le Chatelier flask, and the specific surface area was evaluated with a Blaine air permeability apparatus. Compressive strength tests were carried out on cubic specimens (2×2×2 cm) using a Controls 65-L27 universal testing machine under standard curing conditions.

According to G. I. Knigin's methodology, the reactivity of burnt rocks is characterized by their adsorption activity [15-17]. Rocks burnt at 500-600 °C show the highest activity, while further heating to 800-1000 °C significantly reduces their reactivity. The presence of micropores and microcracks enhances the sorptive and pozzolanic activity of the material. The clay-iron modulus (M) is used to classify the activity of burnt rocks in relation to lime and gypsum [1]:

$$M = \frac{Al_2O_3 + Fe_2O_3}{SiO_2}. \quad (1)$$

Depending on this module, burnt rocks are divided into four activity groups: $M < 0.2$ – monoactive; $M = 0.2\text{-}0.3$ – moderately active; $M = 0.3\text{-}0.45$ – active; $M > 0.45$ – highly active.

Local burnt rocks (glyage) were selected as the main raw material for mixed binder development. Additional components included: gypsum G-4 (GOST 125-2018), Portland cement clinker (KCShK type), fly ash from the Belarusian Thermal Power Plant (BTEC), and construction lime.

The chemical composition of the raw materials is given in Table 1.

Table 1. Chemical composition of the initial raw materials (% by weight)

Materials	Oxide content, in %									
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	l.o.i	Σ
Gliezh	58.64	20.61	8.69	0.97	3.1	0.88	–	–	2.18	–
Portland cement	21.9	5.18	4.70	66.16	1.59	0.58	–	–	0.13	–
Ash BTEC	51.57	21.87	3.70		3.09	1.24	1.47	0.52	16.54	–

The gypsum G-4 used in the experiments corresponds to a high-strength setting class (A). The setting time ranged from 2 to 5 minutes with a normal consistency of 50 %. Its compressive strength was 3.76 MPa, and bending strength was 2.19 MPa.

Construction lime had a slaking temperature of 50 °C, a slaking duration of 33 minutes, and contained 8 % unslaked particles. The total content of active CaO + MgO was 92 %, which classifies it as grade 1 lime.

The mineralogical composition of the fly ash includes both glassy and crystalline phases. The glass phase enhances its hydraulic activity, while the crystalline phase consists mainly of amorphized clay matter, quartz grains, feldspar, calcium and magnesium carbonates, dicalcium silicate, calcium aluminate, and mullite. The characteristic diffraction peaks for quartz ($d = 4.24$; 3.34; 2.77; 1.81 Å), mullite ($d = 3.35$; 2.68; 2.52; 2.19 Å), and calcium carbonate ($d = 3.03$ Å) were identified from the X-ray diffraction patterns.

The granulometric composition of fly ash is presented in Table 2.

Table 2. Granulometric composition of fly ash

No. strength	Residue on sieves, mm								
	10	5	3	2	1	0.5	0.25	0.15	less 0.15
1	11.04	4.26	2.90	3.64	3.21	7.02	6.02	14.55	47.93
2	9.78	5.81	2.53	1.69	4.06	3.57	9.63	12.24	50.63
3	11.16	4.34	3.11	2.02	3.86	2.94	12.16	13.52	46.86

The average density of fly ash was 815-845 kg/m^3, and the specific surface area ranged from 2780 to 3050 cm^2/g.

The Portland cement clinker consisted of the following minerals (%): C_3S – 60.65, C_2S – 16.56, C_3A – 5.74, and C_4AF – 14.80. Its physical and mechanical characteristics are presented in Table 3.

Table 3. Granulometric composition of fly ash

Name of material	Normal density where NG %	Fineness of grinding, % passed through sieve 008	Setting time		Ultimate strength after steaming, MPa		28-day ultimate strength during hardening under normal conditions, MPa	
			Start hour, min	End of hour, min	Bending	Compression	Bending	Compression
Cement KCShK	23,7	88	2h 44m	6h 39m	4.06	21.85	6.02	32.74

In this work, for the first time, glyage was used, the chemical composition of which is given in Table 1.

Visual and microscopic examination of the rock revealed a slate-like layered texture. The brick-red color of the rock is due to the high iron content.

According to the chemical composition, the studied clayey clay belongs to active rocks according to the clay-iron module:

$$M = \frac{Al_2O_3 + Fe_2O_3}{SiO_2} = \frac{20.61 + 8.69}{58.61} \approx 0.5 \succ 0.45. \quad (2)$$

The grindability of the clay was determined by grinding in a laboratory ball mill.

Despite the fact that the hardness on the Mohs scale is 4.5, the rock is ground to a grinding fineness corresponding to the complete passage through a 063 sieve for 3 hours 10 minutes, which can be explained by their genesis: they are characterized by a significant content of microcracks formed during pyroprocesses. In addition, graphite contained in burnt rocks also contributes to the intensification of grinding.

The gluing was tested as a clay raw material. It was found that its plasticity (P) is 7.6 and according to the plasticity number it is classified as a moderately plastic raw material. The physicochemical properties of gluing are given in Table 4.

Table 4. Physicochemical properties of gluing

Properties	Meanings
Total exchange capacity, Mg-eq/100h	26.84
Composition of exchangeable cations, Mg-eq/100 h:	
Ca^{2+}	18.10
Mg^{2+}	5.07
Na^{2+}	3.03
True density	2.61
Swelling, %	40

As can be seen from the data in Table 4, the burnt rock under consideration is characterized by a fairly high total exchange capacity of 26.84 Mg-eq/100 g, which shows the high adsorption capacity of the rock. Moreover, Ca^{2+} prevails in the composition of exchange cations. (18.10 (Mg-ekv)/100g); Mg^{+2} (5,07m^2-ekv/100g). And the exchange ion Na+ Na^+ (3.03 Mg-eq/100g).

3. Results and discussion

Mixed binders of various compositions were developed using local burnt rocks (glyage), lime, gypsum, ash, and small amounts of Portland cement. The composition ratios and the corresponding compressive strength values are summarized in Table 5.

Table 5. Physicochemical properties of gluing

No.	Ratio of components, %					Density	Compressive strength, MPa			
	Gliezh	Lime	Gypsum	Ash	P/C		1 day	3 day	14 day	28 day
1	85	15	–	–	–	1.40	0.495	1.01	1.22	3.08
2	70	30	–	–	–	1.41	2.05	3.59	3.66	12.1
3	80	15	5	–	–	1.46	0.495	2.9	3.16	9.02
4	70	20	10	–	–	1.4	2.45	3.77	5.85	11.82
5	80	10	10	–	–	1.42	0.37	2.9	3.4	9.09
6	60	20	20	–	–	1.43	3.01	9.53	9.6	2.7
7	70	15	–	10	–	1.42	1.2	4.85	3.17	9.45
8	50	20	–	20	–	1.42	1.5	5.07	3.41	10.01
9	80	15	–	–	5	1.40	0.42	1.01	1.20	13.21
10	70	20	–	–	10	1.42	0.44	2.43	3.68	17.61
Note: Small specimens (2×2×2 cm) were tested; actual field strength is estimated to be approximately twice higher										

3.1. Effect of lime content

The test results show that in lime-containing binders, compressive strength increases with the lime content. This is attributed to the intensified formation of calcium hydrosilicates during hardening. With 30 % lime, the highest strength of 12.1 MPa was reached after 28 days. The strength development curve indicates steady growth from 14 to 28 days without any retrogression, confirming the ongoing pozzolanic reaction between lime and active aluminosilicates of the burnt rock.

3.2. Effect of gypsum and ash

Compositions containing 5-20 % gypsum (samples 3-6) exhibited variable behavior. When gypsum content was limited to 10 %, the strength ranged from 9.0 MPa to 11.8 MPa, indicating positive interaction between Fe_2O_3- and Al_2O_3-rich glyage and sulfate ions. However, at 20 %

gypsum, the strength dropped sharply due to excessive sulfate formation and microcracking during hydration.

Compositions with fly ash additions (10-20 %) achieved compressive strengths of 9.4-10.0 MPa. This confirms that ash acts as a strength activator due to its glassy phase, which enhances the pozzolanic reaction. Moreover, ash-containing binders demonstrated improved water resistance and dimensional stability.

3.3. Influence of Portland cement

Partial replacement of lime with 5-10 % Portland cement further increased the 28-day strength up to 17.6 MPa, effectively improving the binder grade from M200 to M300. The cement phase acts as a hydration catalyst, forming additional calcium silicate hydrates (C-S-H), which densify the microstructure.

3.4. Implications for vibration and transport performance

The obtained compressive strength (up to 17.6 MPa) and density values indicate the formation of stiff and compact binders. Static stiffness is directly correlated with the dynamic modulus, which governs vibration transmission and fatigue behavior of pavement layers. Lime-rich compositions exhibit relatively higher damping capacity, enabling better energy dissipation under cyclic loading, while cement- or ash-enriched mixtures increase stiffness, potentially reducing vibration amplitudes but increasing resonance sensitivity.

These results highlight that the selection of binder composition affects not only mechanical durability but also dynamic performance – a critical factor for vibration-resistant road and railway foundations. Future studies should include measurements of dynamic modulus, damping ratio, and fatigue endurance to comprehensively evaluate the vibration mitigation potential of these mixed binders.

3.5. Dynamic implications for vibration control

The compressive strength and density of the developed binders directly affect the dynamic modulus and damping ratio of road materials. Increased stiffness leads to lower vibration transmissibility, while lime-rich compositions improve damping and energy dissipation. These parameters are crucial for designing vibration-resistant transport pavements, where vehicle-induced dynamic stresses are dominant.

3.6. Applicability in transport infrastructure

The developed burnt-rock-based binders can be effectively used in several structural elements of transport infrastructure:

– Base and subbase layers of road pavements, where high stiffness and controlled damping are required to resist dynamic vehicle loads and vibration.

– Subgrade stabilization in weak soils, improving load-bearing capacity and reducing deformation under cyclic loading.

– Railway embankment foundations, providing improved vibration attenuation and long-term durability.

– Precast elements and masonry blocks in auxiliary transport facilities (drainage channels, retaining walls, and edge curbs).

The vibration-damping and stiffness-controlling properties of these binders make them especially applicable in regions with high traffic intensity, near bridges, tunnels, and areas sensitive to vibration transmission.

4. Conclusions

According to the clay-iron modulus, the studied burnt rocks (glyage) belong to the category of active pozzolanic materials, exhibiting high reactivity toward lime and other alkaline components.

The investigated burnt rocks show enhanced grindability due to their fine microcracked structure and the presence of minor graphite inclusions, which facilitate the mechanical activation process.

Several types of mixed binders were successfully developed based on burnt rocks: lime-glyage, lime-glyage-gypsum, lime-glyage-ash, and lime-glyage-cement systems. Their strength classes correspond to M200 and M300, respectively.

The inclusion of industrial by-products such as burnt rocks and fly ash significantly reduces production cost, promotes waste recycling, and expands the raw material base for eco-friendly construction materials.

The developed binders achieved compressive strengths up to 17.6 MPa, making them suitable for masonry units, foundation blocks, road base layers, and subgrade stabilization.

From the viewpoint of transport and vibration engineering, the studied materials demonstrate a favorable combination of stiffness and damping properties, indicating potential for use in vibration-resistant pavement structures and dynamic load-bearing applications.

The overall novelty of this research lies in the first systematic application of locally available burnt rocks in vibration-sensitive transport structures, linking binder composition with dynamic performance and sustainable material design.

The study provides a foundation for future vibration-based performance testing of binders in pavement systems, contributing to the development of vibration-resistant and sustainable transport structures.

The developed burnt-rock-based binders show strong potential for practical use in the construction and rehabilitation of vibration-resistant roads, railways, and transport foundations. Their dual functionality-eproviding both structural strength and vibration damping-making them a promising material for sustainable and resilient transport infrastructure.

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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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