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Vibro-pressed concrete for wall blocks based on lightweight expanded clay aggregate obtained with the addition of oil sludge

Roza Narmanova[1]*, Kylyshbai Bissenov[2], Nargul Saktaganova[2], Sergiy Lyubchyk[3], Nurlybek Kelmagambetov[4]

[1]Laboratory of Engineering Profile "Physical and Chemical Methods of Analysis", Korkyt Ata Kyzylorda University, Kyzylorda, Kazakhstan
[2]Institute of Engineering and Technology, Korkyt Ata Kyzylorda University, Kyzylorda
[3]DeepTechLab, Faculty of Engineering, Lusófona University, Lisbon, Portugal.
[4]Department of Engineering and Logistics, Kyzylorda Bolashak University, Kyzylorda, Kazakhstan
*Correspondence: roza_an@mail.ru

Abstract. This study develops lightweight expanded clay aggregate (LECA) from local low-expanding loams using an oil-sludge-based fuel-containing additive and evaluates its use in vibro-pressed lightweight aggregate concrete (LWAC) wall blocks. LECA was produced by granulation and firing, then characterized by bulk density, water absorption, and compressive strength. LWAC blocks were manufactured via a semi-dry vibro-pressing route and tested for density, compressive strength, thermal conductivity, and freeze-thaw resistance. The LECA incorporating oil sludge showed a strength increase from 1.38 MPa to 2.8-3.1 MPa with a moderate density rise (316 to 350-400 kg/m^3) while maintaining ~25.8% water absorption. Blocks achieved 800-950 kg/m^3 density and 10-12 MPa compressive strength, with 0.75-0.8 W/(m·K) thermal conductivity and 50-75 freeze-thaw cycles. XRD pattern fitting indicated silicate- and spinel-type crystalline phases, though some matches require verification. Overall, the raw material and processing route enable structural wall units with improved thermal performance. The future work should prioritize moisture-related durability under higher saturation.

Keywords: expanded clay aggregate, oil sludge additive, vibro-pressing, lightweight aggregate concrete, thermal insulation wall blocks.

1. Introduction

Improving the energy efficiency of buildings remains a major driver of innovation in wall and envelope materials, because heat losses through external walls strongly affect operational energy demand and life-cycle impacts of the building stock [1]. In many cold and continental climates, the envelope must simultaneously provide (i) adequate load-bearing capacity, (ii) low thermal conductivity, and (iii) long-term durability under freeze-thaw action and moisture exposure. A common approach is to use multilayer systems where a structural wall (e.g., masonry or concrete) is combined with an external insulation system. However, such solutions introduce additional interfaces, workmanship sensitivity, and serviceability/fire-safety considerations that motivate continued interest in single-layer wall units with improved thermophysical performance [2], [3], [4]. Consequently, the development of structural-thermal insulating wall blocks based on lightweight concrete remains an actual research and engineering task.

Lightweight aggregate concrete (LWAC) is widely recognized as an effective route to reduce density and improve thermal performance compared with normal-weight concrete, while retaining sufficient mechanical strength for many structural or semi-structural applications [5]. Among manufactured lightweight aggregates, lightweight expanded clay aggregate (LECA) is particularly important due to its relatively stable production technology and favorable combination of low density, internal porosity, and chemical compatibility with cement matrices [6]. The porous shell-core microstructure of LECA decreases thermal conductivity and can also provide internal curing effects, while the overall performance of LECA concrete depends strongly on aggregate grading, water absorption/pre-wetting practice, and the quality of the interfacial transition zone [5], [6], [7], [8]. Recent studies and overviews show that concretes with expanded clay aggregates can achieve strength levels suitable for structural elements and can contribute to lowering heat transfer through building envelopes, provided that mixture design and moisture control are properly managed [6], [7], [8], [9], [10]. For wall blocks, these considerations are especially important because thermal performance, density class, and water absorption must be balanced against compressive strength and production feasibility.

At the same time, the properties of LECA itself depend on raw material mineralogy and on additives used during firing that affect bloating, pore formation, and the resulting phase composition and microstructure [11], [12]. This is relevant for regions where local low-expanding loams/clays are available but may require formulation adjustments to achieve stable expansion and target density. An additional motivation is sustainability: the incorporation of industrial wastes as pore-forming agents or fuel-containing additives during ceramic processing has been actively explored to reduce environmental burden and potentially improve performance. For example, oily wastes and petroleum/oil-sludge-type residues have been investigated as additives in fired clay ceramics, showing that they can influence firing behavior, porosity development, and final properties when used in controlled dosages [12], [13]. Related work has also demonstrated the feasibility of using waste engine oil (a fuel-rich waste) as an expansive additive in the production of expanded clay aggregates and has evaluated the effects of such aggregates on the physical and mechanical properties of lightweight concretes [14]. These findings support the broader idea that oil-derived wastes can be valorized in fired clay/ceramsite-type products, but the optimal dosages and processing routes remain highly system-specific and must be validated for the targeted wall products.

A further practical dimension is the manufacturing route of wall blocks. In industrial practice, many masonry and wall units are produced using low-slump or semi-dry mixtures under vibro-pressing/vibro-compaction (simultaneous vibration and pressing), because this method enables fast demolding, dimensional stability, and high productivity [15], [16], [17]. However, the compaction regime, moisture content, and grading are known to significantly affect density, pore connectivity, and consequently both strength and thermophysical properties of the final blocks [15], [16], [17], [18]. While a substantial body of research addresses cast LWAC (including self-compacting variants) [9], fewer studies provide a clear linkage between (i) locally produced expanded clay aggregate characteristics (including phase composition), (ii) semi-dry vibropressed block production parameters, and (iii) the resulting strength-density-thermal conductivity balance required for energy-efficient wall blocks.

Within this context, the present study is important because it targets an applied but scientifically grounded task: developing and experimentally validating vibro-pressed structural-thermal insulating wall blocks made with LECA produced from local raw materials (including low-expanding loam) with the use of an oil-sludge-type additive acting as a fuel-containing/pore-forming component during aggregate production. The goal of the work is to substantiate whether such a combination of local loam-based expanded clay aggregate and vibro-pressed cementitious mixtures can yield wall blocks that meet the required mechanical and thermophysical criteria. To achieve this goal, the study focuses on: characterizing the expanded clay aggregate (including mineral/phase features relevant to firing and performance); producing vibro-pressed expanded-clay concrete blocks using a semi-dry technology consistent with industrial practice; and evaluating key properties (density class, compressive strength, water absorption, and thermal performance indicators) needed to justify the feasibility of the proposed wall unit concept for energy-efficient construction.

2. Methods

The research objects were LECA and experimental samples of thermal insulation-structural wall blocks produced by semi-dry vibro-pressing from a blend of LECA, M400 cement, and dune sand. The determination of the physical, mechanical, and thermal properties of the blocks was carried out in accordance with [19]. The following raw materials were used: M400 cement as binder complying with [20], dune sand from Kyzylorda deposit (Kyzylorda region, Kazakhstan) as fine aggregate complying with [21], and LECA from Kyzylorda deposit (Kyzylorda region, Kazakhstan) as coarse aggregate complying with [22] with a maximum particle size not exceeding 20 mm. LECA was produced from low-expanding loams using oil sludge as a fuel-containing bloating/pore-forming reagent, based on our previous experience [23], [24]. To facilitate the incorporation of the bloating component, an “oil sludge-dune sand” conglomerate was prepared at a 1:3 proportion, using oil sludge from JSC “PetroKazakhstan Kumkol Resources” (Kyzylorda, Kazakhstan) and the aforementioned dune sand. A pilot batch of 10 m^3 of the LECA has been prepared at the “Stroykombinat” LLP (Uralsk, Kazakhstan) and tested along with conventional LECA (existing in the market), to obtain their physical and mechanical properties according to [22].

For manufacturing the LWAC blocks, the concrete mixture composition (per 1 m^3) consisted of cement – 250 kg, expanded clay (10-20 mm fraction) – 660 kg, sand – 340 kg, and water – 95-100 liters. The average percentage proportion of the biner-aggregates was: cement – 20%, sand – 27%, and LECA – 57%. Before pilot production, mixture compositions were simulated at laboratory scale to obtain effective physical, mechanical, and thermophysical performance, based on prepared samples. Reduced-density thermal insulation-structural blocks of standard size of 390×190×188 mm were then manufactured on the “Mastek-Meteor” molding/vibro-pressing complex (Figure 1) produced by ZAO “Monolit” (Zlatoust, Russia).

Figure 1 – LWAC blocks manufacture using the “Mastek-Meteor” molding/vibro-pressing complex

In production, the reagents were weighed and loaded into the mixer of the “Mastek-Meteor” unit, where water was added, and the mixture was blended to obtain a semi-dry homogeneous mass. The mixture was then transferred to the unit hopper-doser, portioned, and supplied to the mold matrix. Shaping was performed by vibrocompression, forming a level and dense layer of expanded clay particles, water, and cement; three blocks were produced simultaneously, after which the molded blocks were manually removed with pallets and transported for natural curing.

The thermal conductivity of the samples was determined using an ITP-MG-4 "ZOND" thermal conductivity meter (SKB StroyPribor, Chelyabinsk, Russia). X-ray diffraction (XRD) of LECA and LWAC samples was performed using a Rigaku MiniFlex 600 diffractometer (Rigaku Corporation, Akishima-shi, Tokyo, Japan) with CuKα radiation in the 2θ range from 3° to 120°, and the collected data were processed using the PDF-5+ 2024 database.

3. Results and Discussion

Table 1 shows that the proposed LECA formulation improves aggregate strength while maintaining a broadly similar firing regime.

Table 1 – Effect of the developed formulation on LECA properties (pilot-industrial batch)

LECA type	Firing temperature, °C	Compressive strength, MPa	Bulk density, kg/m^3	Water absorption, %
Conventional	1200	1.38	316	25.85
Proposed	1150-1200	2.8-3.1	350-400	25.8

In Table 1, the most important change is compressive strength: it increases from 1.38 MPa to 2.8-3.1 MPa, which suggests the proposed formulation produces granules that are less prone to crushing during handling and concrete mixing. Bulk density also increases from 316 to 350–400 kg/m^3, indicating a trade-off toward a denser aggregate, which often accompanies higher strength in expanded clay systems. This direction is consistent with the general LECA overview that strength and density are strongly controlled by formulation and firing outcomes, including the balance between shell densification and internal porosity [6]. Water absorption remains essentially unchanged (25.85% vs. 25.8%), meaning the pore network accessible to water is not materially reduced. That is important for later concrete production, because high absorption typically requires moisture control or water adjustment to avoid variability in workability and matrix quality.

Table 2 summarizes the key performance envelope of the developed LWAC blocks as a structural-thermal material.

Table 2 – Physical, mechanical, and thermal properties of LWAC

Thermal conductivity, W/(m·K)	Density, kg/m^3	Water absorption, %	Compressive strength, MPa	Frost resistance, cycles
0.75-0.8	800-950	23-25	10-12	50-75

The reported density of 800-950 kg/m^3 confirms that the product is in the lightweight range, which is consistent with using expanded clay aggregate and with the general aim of reducing unit weight in wall elements [5]. The compressive strength of 10-12 MPa indicates that the blocks are positioned for load-bearing or at least structurally relevant masonry applications rather than purely insulating units, and this strength level is in line with the expectation that expanded-clay lightweight concretes can be designed to reach structural grades when mixture design and moisture management are controlled [6]. Thermal conductivity of 0.75-0.8 W/(m·K) suggests that the blocks provide a thermophysical improvement compared with dense concretes, but the value is still relatively high for a "single-layer" wall solution, so in practice the blocks may serve best as structural units with improved thermal performance rather than as a stand-alone high-insulation material. This is consistent with the fact that thermal conductivity in cementitious materials is strongly influenced by density and pore structure [7]. Water absorption of 23-25% is high, which implies an open pore network and highlights the importance of moisture-related durability, because higher absorption can increase susceptibility to freeze-thaw damage if saturation occurs. Therefore, the reported frost resistance of 50-75 cycles is an important supporting result for serviceability in cold climates.

Figure 2 presents the XRD diffractogram of the fired expanded clay (i.e., proposed LECA). The red curve is the measured diffraction pattern, while the colored reference markers correspond to the phases selected by the identification software/database and used to fit the experimental peaks. The legend also reports the phase fractions obtained from the software's semi-quantitative evaluation.

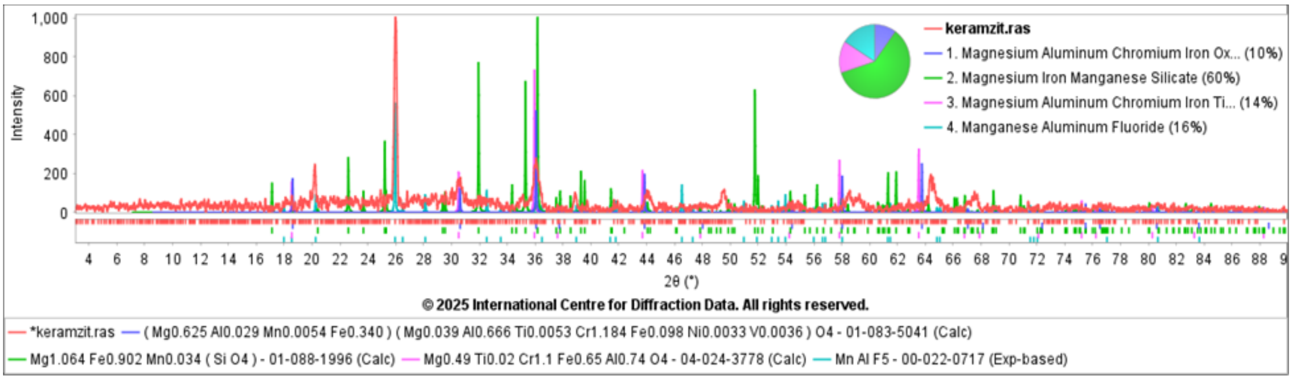

Figure 2 – Diffractogram of LECA

The pattern indicates that the expanded clay is not purely glassy; it contains a clear crystalline fraction. The dominant contribution in Figure 1 is the magnesium–iron–manganese silicate phase, reported as about 60%, because many of the strongest peaks align with that reference pattern. Two cubic spinel-type mixed oxides (Al–Cr–Fe–Mg–O with minor Ti) are also present and together account for a noticeable part of the fitted intensity (reported as 10% and 14%). These spinel-type phases are consistent with high-temperature firing, where Al- and Fe-bearing components of the raw clay can transform into stable mixed oxides. The diffractogram also reports a manganese aluminum fluoride contribution (about 16%). This identification is possible in peak-matching terms, but it is unusual for clay-derived LECA unless a fluorine source exists, so it should be treated as provisional until supported by chemistry or repeated fitting with alternative candidates.

Table 3 lists the phases identified in LECA and provides their crystallographic descriptors.

Table 3 – Phase identification results from XRD pattern fitting of LECA

No.	Compound name	Chemical formula	Crystal system	a (Å)	b (Å)	c (Å)	Unit-cell volume V (Å³)	Z	Space group	X-ray density ρ (g/cm³)
1	Magnesium aluminum chromium iron oxide (spinel)	$Al_{0.695}Cr_{1.184}Fe_{0.438}Mg_{0.664}O_4$	Cubic	8.25	–	–	561.74	8	Fd-3m	8.25
2	Magnesium aluminum chromium iron titanium oxide (spinel)	$Al_{0.74}Cr_{1.10}Fe_{0.65}Mg_{0.49}Ti_{0.02}O_4$	Cubic	8.28	–	–	567.27	8	Fd-3m	4.46
3	Magnesium iron manganese silicate	$(Fe_{0.902}Mg_{1.064}Mn_{0.034})_2SiO_4$	Orthorhombic	4.79	10.34	6.04	299.49	4	Pbnm	3.77
4	Manganese aluminum fluoride	$MnAlF_5$	Orthorhombic	9.54	9.85	3.58	336.41	–	Amam	–

Table 3 confirms that phases 1 and 2 are cubic spinels (space group Fd-3m) with very similar lattice constants (a about 8.25–8.28 Å), which supports the interpretation that they represent a family of closely related high-temperature mixed oxides. In practice, such phases are generally chemically stable and can contribute to the aggregate’s mechanical integrity. Phase 3 is an orthorhombic (Pbnm) magnesium-iron-manganese silicate with a, b, c values consistent with an olivine-type silicate. This matches the fact that it is the dominant phase in Figure 2 and is a plausible high-temperature product of silicate systems after firing. Phase 4 is reported as AlF_5Mn (orthorhombic, Amam). Because fluorides are not typical products of firing ordinary loams, this phase comes from database matching and requires confirmation. Overall, Figure 2 and Table 3 together support a fired LECA structure composed of a crystalline assemblage dominated by silicates with a secondary fraction of spinel-type oxides, which is consistent with a thermally treated clay-based ceramic aggregate rather than an amorphous material.

Figure 3 shows the XRD pattern of the LWAC. The red curve is the measured intensity versus 2θ, and the colored reference lines/markers correspond to the phases selected during pattern fitting. The pie chart in the figure reports the software-estimated phase fractions for the fitted set.

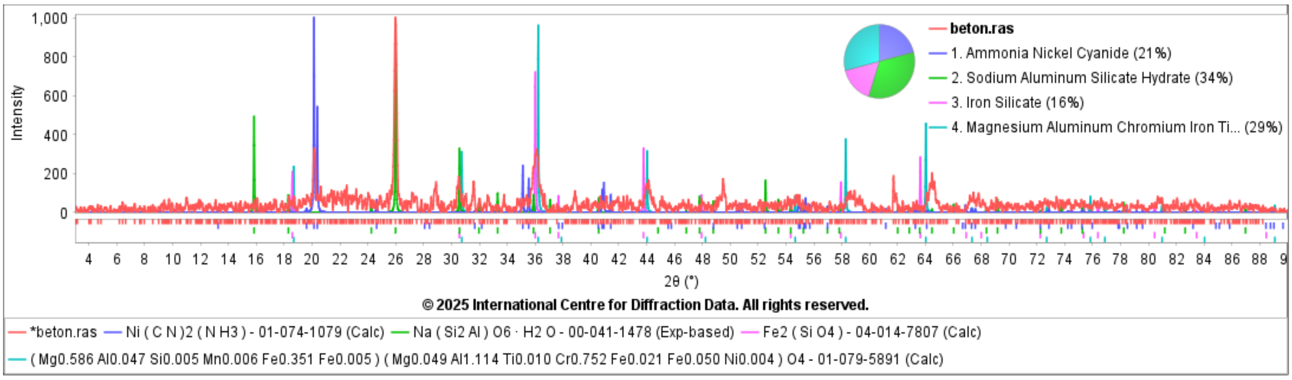

Figure 3 – Diffractogram of LWAC

From Figure 3, the LWAC sample is clearly not fully amorphous. Several sharp peaks indicate distinct crystalline contributions. The fitted phase set is dominated by a "sodium aluminum silicate hydrate" component (reported as 34%) and a spinel-type mixed oxide phase (reported as 29%). Such aluminosilicate-bearing phases are plausible in a system containing fired clay-based aggregate, since fired LECA commonly contains stable crystalline silicate constituents formed during high-temperature processing [6]. The spinel-type oxide contribution is also consistent with the idea that high-temperature firing of clay-based raw materials can yield stable mixed-oxide phases that remain present when the aggregate is incorporated into concrete [11]. Figure 3 also assigns about 16% to "iron silicate" and about 21% to a Ni-C-N phase ("ammonia nickel cyanide" in the figure legend). That last identification is unusual for cement/LECA-based concrete unless there is a credible nickel source, so it should be treated as a tentative match rather than a confirmed reaction product.

Table 4 lists the phases identified in LWAC and provides their crystallographic descriptors.

Table 4 – Phase identification results from XRD pattern fitting of LWAC

No.	Compound name	Chemical formula	Crystal system	a (Å)	b (Å)	c (Å)	Unit-cell volume V (Å³)	Z	Space group	X-ray density ρ (g/cm³)
1	Nickel cyanamide (as reported; requires verification)	$NiCN_2$	Tetragonal	7.22	–	17.42	908.58	8	I41/amd	1.86
2	Iron silicate (spinel-type, fayalite-related notation fixed)	Fe_2SiO_4	Cubic	8.26	–	–	564.46	8	Fd-3m	4.79
3	Magnesium aluminum chromium iron titanium oxide (spinel)	$Al_{1.161}Cr_{0.752}Fe_{0.427}Mg_{0.635}Ti_{0.01}O_4$	Cubic	8.22	–	–	555.19	8	Fd-3m	4.18
4	Analcime	$NaAlSi_2O_6{\cdot}H_2O$	Cubic	13.71	–	–	2575.13	16	Ia-3d	2.27

Table 4 indicates that two of the identified phases are cubic spinel-structured oxides (Fd-3m) with lattice parameters around 8.22-8.26 Å. This supports the interpretation that a portion of the crystalline signal in LWAC comes directly from the fired aggregate, because spinel-type mixed oxides are typical high-temperature products in clay-derived ceramics and can persist unchanged in the concrete composite [11]. Analcime is a crystalline sodium aluminosilicate hydrate (a zeolite). Its presence could be consistent with an aluminosilicate framework phase in a system containing clay-derived components and alkaline pore solutions, but the manuscript cannot claim a formation mechanism from XRD fitting alone. The $NiCN_2$ assignment remains the weakest point: it is difficult to reconcile with the intended raw materials of LWAC, so it should be flagged as needing verification against alternative database matches, especially because cementitious systems often contain crystalline hydrates (for example, portlandite or ettringite) that may be missed or misassigned if the fitting is constrained. This matters for interpretation because the reviewed literature emphasizes that performance in LWAC depends strongly on mixture design, moisture control, and microstructure rather than on any single unusual crystalline phase [5].

4. Conclusions

Lightweight expanded clay aggregate (LECA) produced from local low-expanding loams with an oil-sludge-based fuel-containing additive provided a clear mechanical advantage: its compressive strength increased from 1.38 MPa to 2.8-3.1 MPa, while bulk density rose moderately (316 to 350-400 kg/m^3) and water absorption stayed nearly unchanged (~25.8%). Using this LECA in vibro-pressed lightweight aggregate concrete (LWAC) wall blocks resulted in a lightweight density of 800-950 kg/m^3 and compressive strength of 10-12 MPa, with 0.75-0.8 W/(m·K) thermal conductivity and 50-75 freeze-thaw cycles, confirming applicability as structural wall units with improved thermal performance. XRD-based phase fitting indicates the presence of mainly spinel-type and silicate-related crystalline phases in LECA/LWAC; however, several identified matches should be treated as provisional and verified by complementary analyses. Future work should primarily address moisture sensitivity (high water absorption), including optimization of curing/conditioning and durability testing under higher saturation and service-relevant exposure regimes.

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Information about authors:

Roza Narmanova – Candidate of Technical Sciences, Docent, Laboratory of Engineering Profile "Physical and Chemical Methods of Analysis", Korkyt Ata Kyzylorda University, Kyzylorda, Kazakhstan, roza_an@mail.ru
Kylyshbai Bissenov – Doctor of Technical Sciences, Professor, Institute of Engineering and Technology, Korkyt Ata Kyzylorda University, Kyzylorda, Kazakhstan, bisenov_ka@mail.ru
Nargul Saktaganova – PhD, Institute of Engineering and Technology, Korkyt Ata Kyzylorda University, Kyzylorda, amanovna.75@mail.ru
Sergiy Liubchik – PhD, DeepTechLab, Faculty of Engineering, Lusófona University, Lisbon, Portugal, p6349@ulusofona.pt
Nurlybek Kelmagambetov – Candidate of Technical Sciences, Department of Engineering and Logistics, Kyzylorda Bolashak University, Kyzylorda, Kazakhstan, nkelmagambetov@mail.ru

Author Contributions:

Roza Narmanova – resources, data collection, editing, drafting, funding acquisition
Kylyshbai Bisenov – concept, methodology.
Nargul Saktaganova – testing, interpretation.
Sergiy Lyubchyk – analysis.
Nurlybek Kelmagambetov – modeling, visualization.

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