



Review

Hyper-pressing technologies and properties of construction products: a review

Ruslan Nurlybayev¹, Maratbek Zhuginissov², Yelzhan Orynbekov¹, Yerlan Khamza¹,
 Yerlan Kushekov^{1,*}

¹“Technopark Stroytech” Scientific Research Laboratory of Construction and Building Materials, Satbayev University, Almaty, Republic of Kazakhstan

²Bassenov Institute of Architecture and Civil Engineering, Satbayev University, Almaty, Republic of Kazakhstan

*Correspondence: kush_er@mail.ru

Abstract. High-pressure forming is increasingly recognized as a promising method for producing low-energy masonry units from natural minerals and secondary raw materials. This review consolidates current knowledge on compressed earth blocks, cementitious high-pressure bricks, alkali-activated products, and ultra-high-pressure waste-derived bricks. Emphasis is placed on raw material selection, mixture preparation, forming moisture, compaction pressure, curing conditions, structure formation mechanisms, and resulting engineering properties. The literature indicates that pressure-induced particle rearrangement and pore reduction must be integrated with hydration, pozzolanic reactions, alkali activation, or carbonation to achieve stable long-term performance. Increasing pressure typically enhances density, strength, and water resistance up to an effective densification threshold, beyond which further pressure may yield limited benefits or induce microcracking and elastic recovery. Industrial, mining, construction, and agricultural wastes can substitute for significant proportions of natural raw materials; however, their use necessitates careful control of particle grading, chemical variability, soluble salts, and potentially hazardous components. The environmental advantages of avoiding firing may be offset by high Portland cement content, extended transport distances, and energy-intensive waste pretreatment. This review highlights insufficient standardization of terminology, specimen geometry, compaction procedures, curing regimes, and durability assessment as major obstacles to comparison. Future research should focus on long-term exposure testing, full-scale production, environmental safety, life-cycle assessment, and the development of low-carbon binder systems.

Keywords: high-pressure-formed bricks, unfired masonry, compressed earth blocks, waste-derived bricks, industrial waste, compaction pressure, structure formation, durability, life-cycle assessment.

1. Introduction

Bricks are widely utilized masonry materials due to their durability, fire resistance, dimensional versatility, and relatively straightforward production. However, conventional fired-brick manufacturing consumes significant quantities of natural clay and energy and generates greenhouse gases and particulate emissions [1]. These environmental challenges, combined with the increasing accumulation of industrial and mining waste, have prompted the development of unfired, low-energy masonry products incorporating secondary raw materials [2], [3].

A diverse array of waste materials, such as fly ash, metallurgical slag, mine tailings, quarry residues, recycled glass, wastewater treatment sludge, and agricultural by-products, has been explored for brick production. Incorporating these materials can reduce landfill disposal and decrease the consumption of virgin raw materials [4]. However, the properties of the resulting bricks depend heavily on the chemical and mineralogical composition of the waste, particle-size distribution, moisture content, forming method, and curing conditions [5]. Consequently, waste-containing bricks should not be evaluated solely based on the type or dosage of the incorporated residue.

Brick products can be manufactured using various methods, including extrusion, molding, pressing, firing, autoclaving, cementitious hardening, and geopolymerization. Among these techniques, high-pressure compaction is particularly promising because it produces dense, geometrically precise products from relatively dry mixtures. Higher compaction pressures promote particle rearrangement, reduce internal voids, increase interparticle contact areas, and enhance the green density and strength of the compacted material [6].

Rozina and Shestakov [7] demonstrated that increasing pressing pressure from 10 to 100 MPa enhances the density, green strength, drying behavior, and final mechanical performance of ceramic products. Pressures above 60 MPa enable the production of high-strength materials, even when utilizing low-plasticity raw materials and industrial wastes. Recent studies have demonstrated the potential of ultra-high-pressure forming for various industrial waste systems. Ren et al. [8] applied pressures of 100–400 MPa to mixtures of aluminum ash and calcium carbide slag, whereas Chen et al. [9] produced bricks from 100% calcium carbide slag within the same pressure range. Both studies reported high mechanical performance and good water resistance, although the raw-material systems and hardening conditions differed substantially. Recent reviews emphasize that compressed earth blocks and high-pressure bricks represent related yet distinct categories of pressed masonry materials. Compressed earth blocks are primarily soil-based and depend on clay cohesion with or without stabilization, whereas high-pressure bricks may contain minimal natural soil and derive their properties from intensive compaction combined with cement hydration, alkali activation, or carbonation. This distinction is significant because similar terminology is often applied to materials with substantially different compositions, manufacturing conditions, and performance requirements [2], [10], [11]. Fly ash is regarded as a promising component for high-pressure bricks due to its fine particle size and potential pozzolanic activity. A recent study in Kazakhstan demonstrated that thermal power plant ash can be incorporated into high-pressure bricks at up to 40% by mass of the binder, while maintaining a compressive strength grade of at least M150, corresponding to a nominal compressive strength of approximately 15 MPa [12].

Despite growing research interest, the existing literature remains fragmented. The terms high-pressure brick, compressed brick, high-pressure-compacted brick, and ultra-high-pressure contact-molded brick are frequently used to refer to materials with differing raw compositions, pressure levels, curing conditions, and hardening mechanisms [13]. Additionally, most studies focus on short-term compressive strength, while durability, water resistance, thermal properties, environmental safety, standardization, and industrial scalability are examined less frequently [13], [14].

Accordingly, this review seeks to systematize current knowledge on high-pressure bricks, with particular emphasis on raw-material classification, manufacturing and compaction parameters, structure-formation mechanisms, physical and mechanical properties, durability, and environmental and practical considerations. The review also identifies existing research gaps and outlines priority directions for the further development and industrial application of high-pressure masonry materials.

2. Methods

A structured narrative literature review was conducted, informed by the main principles of the PRISMA framework for literature identification, screening, and selection. Full PRISMA reporting was not applied because the review was designed as a comparative narrative synthesis rather than a formal systematic review or meta-analysis. Comparable methodologies have been utilized in recent reviews addressing compressed earth blocks, waste-modified masonry materials, and environmental assessment of earth-based construction [15], [16], [17].

The literature search was performed using Scopus, Web of Science, ScienceDirect, Dimensions, and Google Scholar. The search covered journal articles, review papers, and relevant conference proceedings published in English and Russian. The following keywords and their combinations were used: “high-pressure brick”, “hyper-pressed brick”, “high-pressure compacted brick”, “compressed brick”, “compressed earth block”, “ultra-high-pressure contact molding”,

“industrial waste brick”, “compaction”, “curing”, “microstructure”, “compressive strength”, “water absorption”, “durability”, “thermal conductivity”, and “environmental impact”.

Additional publications were identified through backward and forward reference searching. This snowballing technique facilitated the identification of relevant studies not retrieved during the initial database search. Studies were included if they provided information on at least one of the following aspects: raw-material composition, waste incorporation, mixture preparation, forming moisture, pressing pressure, compaction procedure, curing conditions, structure formation, physical and mechanical properties, durability, thermal performance, environmental safety, or industrial application. Research on cement-based high-pressure bricks, ultra-high-pressure waste bricks, compressed earth blocks, and semi-dry-pressed ceramic products was considered when it contributed to understanding high-pressure compaction mechanisms. Studies unrelated to pressed masonry products or lacking sufficient information on materials and manufacturing conditions were excluded.

For each selected publication, the following data were extracted: authorship and publication year; raw-material and binder type; waste origin and replacement level; particle-size characteristics; moisture content; pressing pressure and forming method; specimen dimensions; curing or firing conditions; test standards; density; water absorption; compressive and flexural strength; durability indicators; thermal properties; microstructural characterization; leaching behavior; and environmental or economic assessment.

Balancing the analyzed performance indicators was prioritized. Previous systematic reviews indicate that compressive strength is reported in most studies on compressed earth products, while thermal conductivity, shrinkage, long-term durability, fire resistance, and sustainability indicators are investigated less frequently. Consequently, studies addressing these underrepresented properties were included even if their material systems differed from conventional cementitious high-pressure bricks [15], [18].

Methodological completeness was evaluated based on the reporting of raw-material characterization, mixture proportions, compaction pressure, curing conditions, specimen geometry, testing procedures, number of specimens, and variability of results. This approach aligns with recent reviews that have identified insufficient reporting and non-standardized experimental procedures as significant obstacles to comparing compressed masonry materials.

Due to substantial differences in raw materials, pressure ranges, specimen dimensions, curing regimes, and testing standards, the results were analyzed through a comparative narrative synthesis rather than a statistical meta-analysis. Extracted information was organized by raw-material classification, manufacturing and compaction parameters, structure-formation mechanisms, performance properties, and environmental and practical aspects. Where feasible, values were converted into consistent units to facilitate comparison between studies.

3. Classification and raw materials of high-pressure-formed bricks

High-pressure-formed bricks represent a diverse category of masonry units manufactured through static compaction of low-moisture mixtures. The literature references several related terms, such as compressed earth blocks, compressed stabilized earth blocks, high-pressure bricks, unfired bricks, and ultra-high-pressure contact-molded bricks. These materials exhibit significant differences in composition, pressing pressure, curing conditions, and hardening mechanisms. Consequently, classification should be based on both the primary raw material and the mechanism of structure formation, as demonstrated in Table 1.

3.1. Main categories of high-pressure-formed bricks

The first group comprises unstabilized compressed earth blocks (CEBs), which are primarily produced from soil containing sand, silt, and clay. The structural integrity of these blocks is achieved through particle compaction, clay cohesion, capillary forces, and drying [19]. While pressing

enhances density and strength relative to traditional adobe, unstabilized blocks typically remain susceptible to water [20].

The second group consists of compressed stabilized earth blocks (CSEBs), which incorporate cement, lime, gypsum, slag-based binders, or other additives to enhance strength and durability. Cement facilitates relatively rapid strength development, while lime is generally more effective in clay-rich soils and promotes long-term pozzolanic reactions [21].

The third group comprises cementitious high-pressure bricks, which are typically manufactured from mineral fillers, Portland cement, water, and chemical or coloring admixtures. Limestone screenings, quartz sand, quarry fines, and industrial mineral residues often serve as the principal solid components. In contrast to conventional CSEBs, these products may contain minimal or no natural soil [22].

The fourth group comprises alkali-activated pressed bricks, in which aluminosilicate-rich precursors such as fly ash, ground granulated blast-furnace slag (GGBS), red mud, or recycled concrete fines are activated using alkaline solutions or calcium-rich components. Their structure develops through the formation of alkali-activated binding gels, while mechanical pressing improves particle contact, reduces porosity, and enhances the interaction between the precursor and activator. Depending on precursor chemistry, these systems may be described more specifically as geopolymer or alkali-activated bricks [23], [24].

The fifth group consists of ultra-high-pressure waste-derived bricks, which are produced at pressures ranging from approximately 100 to 400 MPa [9]. Industrial residues may constitute the majority or entirety of the raw material. For instance, Chen et al. [9] produced bricks from 100% calcium carbide slag, whereas Ren et al. [8] utilized a combination of aluminum ash and calcium carbide slag. In these systems, intensive densification is supplemented by carbonation, curing, or limited chemical reactions.

Pressed bricks that undergo subsequent firing constitute a related but distinct category, as their final structure is primarily formed through sintering rather than hydration or ambient-temperature bonding.

Table 1 – Classification of high-pressure-formed bricks

Brick category	Main raw materials	Main hardening mechanism	Distinctive features
CEBs	Natural soil, sand, silt and clay	Mechanical compaction, clay cohesion and drying	Usually produced without hydraulic binders; relatively sensitive to water
CSEBs	Soil with cement, lime, gypsum or slag-based binders	Compaction combined with hydration, pozzolanic reactions or carbonation	Higher strength and water resistance than unstabilized CEBs
Cementitious high-pressure bricks	Limestone screenings, quartz sand, quarry fines, cement and water	Intensive compaction and cement hydration	Low-moisture mixtures, dense structure and accurate geometry
Alkali-activated pressed bricks	Fly ash, GGBS, red mud, recycled concrete powder and alkaline activators	Formation of alkali-activated binding gels, including geopolymeric gels in suitable aluminosilicate systems	High potential for replacing natural raw materials with industrial wastes
Ultra-high-pressure waste-derived bricks	Calcium carbide slag, aluminum ash and other industrial residues	Extreme densification combined with curing or carbonation	Waste may constitute most or all of the solid raw material; forming pressures may reach 100–400 MPa
Pressed and subsequently fired bricks	Clay, stone-processing wastes, ash and other mineral additives	Compaction followed by sintering	Related technology, but the final structure is formed mainly during firing

Note: CEBs were classified based on studies of soil composition, compaction, and moisture sensitivity [19], [20]; CSEBs – based on cement-, lime-, and waste-stabilized earth systems [21], [25]; cementitious high-pressure bricks – based on studies of pressure-assisted cementitious brick production and mineral fillers [6], [22], [26]; alkali-activated pressed bricks – based on slag- and recycled-concrete-fine systems [23], [24]; ultra-high-pressure waste-derived bricks –

based on aluminum-ash-calcium-carbide-slag and calcium-carbide-slag systems [8], [9]; and pressed-and-fired bricks – based on high-pressure ceramic and earth-hyper-compaction studies [7], [13].

3.2. *Natural soils and mineral components*

Natural soil serves as the primary raw material for CEBs and CSEBs. Sand and gravel constitute the load-bearing framework, silt occupies intermediate voids, and clay imparts cohesion and plasticity [27]. Optimal soil compositions are typically reported as approximately 55–75% sand and gravel, 15–30% silt, and 10–30% clay. However, soils outside these ranges can also be used after grading correction or stabilization [25].

The behavior of clay-rich materials is influenced not only by the proportion of clay present but also by its mineralogical composition and specific surface area. Kaolinite, illite, smectite, and chlorite exhibit distinct properties in terms of plasticity, swelling potential, and interactions with binders. For example, Muheise-Araalia and Pavia [28] demonstrated that illitic clay is suitable for use in unfired masonry, although its high specific surface area diminishes the effectiveness of lime stabilization by increasing the adsorption of calcium ions.

In the production of cementitious high-pressure bricks, soil can be partially or entirely substituted with quartz sand, limestone screenings, crushed stone, or quarry dust. The incorporation of these materials enhances particle packing and dimensional stability. However, an excessive proportion of fine particles may elevate water demand and decrease compaction efficiency [26].

3.3. *Binders and stabilizers*

Portland cement is the most widely used stabilizer for compressed earth and unfired brick systems because it improves early strength, water resistance, and durability [2], [21], [22]. Lime is particularly effective for clay-rich soils and can promote long-term pozzolanic reactions, although its efficiency depends strongly on clay mineralogy [21], [28]. GGBS can be used in combination with cement, lime, or alkaline activation to provide additional hydraulic or pozzolanic binding [2], [23].

Alkaline activators, particularly sodium hydroxide and sodium silicate, are used to activate aluminosilicate-rich precursors in alkali-activated and geopolymer brick systems [2], [23]. Calcium-rich industrial residues, including calcium carbide slag, can additionally contribute reactive calcium and high alkalinity, thereby supporting binder formation and subsequent curing reactions [8], [9].

3.4. *Industrial and construction wastes*

Fly ash is among the most extensively studied industrial by-products for high-pressure-formed bricks. Its role varies with fineness and chemical composition, serving as a filler, pozzolan, cement substitute, or aluminosilicate precursor. Thermal power plant ash has replaced up to 40% of the binder in high-pressure bricks without compromising strength requirements. Other suitable residues include slags, red mud, alumina waste, phosphogypsum, incineration ash, industrial sludge, and calcium carbide slag [12]. The effectiveness of these materials depends on their reactive silica, alumina, calcium, and alkali content, while chlorides, fluorides, soluble salts, and trace metals require careful control [8]. For instance, alumina waste has been combined with lateritic soil and cement to enhance the performance of unfired bricks [29], and calcium carbide slag provides fine, calcium-rich particles that facilitate compaction, carbonation, and binder formation [8], [9]. Construction and demolition waste is processed into recycled concrete fines, crushed brick, ceramic powder, or mixed concrete-brick particles, which serve as replacements for soil, sand, filler, or binder components. Recycled concrete waste has been incorporated at levels up to 50%, while ceramic waste use is constrained by increased water demand and reduced workability [30].

3.5. *Agricultural and biomass-derived materials*

Agricultural residues can be used as fibers, lightweight particles, or ashes. Materials such as straw, hemp, palm fibers, and sawdust, which are lignocellulosic, can reduce density and thermal conductivity while limiting cracking. However, their high water absorption often increases porosity and weakens the fiber-matrix interface (Table 2).

Agricultural ashes, such as rice husk ash, palm-oil fuel ash, sugarcane bagasse ash, and biomass gasification ash, can provide silica-rich reactive phases. The effectiveness of these ashes depends on combustion conditions, fineness, loss on ignition, and residual carbon content. Palm-oil fuel ash contributes through both filler action and limited secondary cementation, whereas biomass gasification ash requires comprehensive chemical and environmental characterization before use [17], [31].

Table 2 – Main raw-material groups used in high-pressure-formed bricks

Raw-material group	Typical examples	Function in the mixture	Main limitations
Natural soils and clays	Sandy soil, silty soil, illitic clay, lateritic soil	Provide cohesion, plasticity and the basic mineral skeleton	Variable composition, shrinkage and moisture sensitivity
Natural mineral fillers	Quartz sand, limestone screenings, quarry dust and crushed stone	Improve grading, packing density and dimensional stability	Excessive fines may increase water demand
Conventional mineral binders	Portland cement, lime and gypsum	Improve strength, water resistance and durability	Cost and environmental impact
Latent hydraulic and alkali-activated materials	GGBS, fly ash, red mud and alumina-rich residues	Participate in pozzolanic or alkali-activation reactions	Often require chemical or calcium-rich activation
Energy and industrial wastes	Fly ash, calcium carbide slag, aluminum ash and phosphogypsum	Replace natural materials and may provide reactive calcium or aluminosilicates	Soluble salts, alkalinity and possible hazardous elements
Construction and demolition wastes	Recycled concrete fines, crushed bricks and ceramic powder	Replace soil, sand, filler or part of the binder	High porosity, water absorption and variable composition
Stone-processing wastes	Granite sludge, marble powder and limestone dust	Act mainly as fine mineral fillers	Excessive content may increase porosity or reduce strength
Agricultural and biomass-derived materials	Straw, fiber, rice husk ash and biomass ash	Reduce density and thermal conductivity or provide reactive silica	High water absorption, organic matter and variable ash quality

Note: natural soils and clays were summarized from studies on compressed earth and illitic-clay bricks [27], [28], [29]; natural mineral fillers – from studies involving quarry-derived mineral materials [26]; conventional hydraulic/mineral binders – from cement-, lime-, and stabilized-earth systems [2], [21], [25], [30]; latent hydraulic and alkali-activated materials – from slag-, fly-ash-, and alumina-containing systems [2], [23], [29]; energy and industrial wastes – from fly-ash-, calcium-carbide-slag-, and aluminum-ash-based bricks [8], [9], [12]; construction and demolition wastes – from recycled concrete and crushed-brick systems [25], [30]; stone-processing wastes – from marble- and quarry-derived mineral residues [26], [32]; and agricultural and biomass-derived materials – from studies on biomass ash and natural-origin additions [17], [31].

The effects of agricultural and organic wastes vary considerably with their physical form. Fibers generally provide crack bridging and reduce density, whereas finely divided ashes may act as fillers or as sources of reactive silica. Consequently, the origin, particle size, residual carbon content, and dosage of these materials should be reported explicitly, since similar waste categories can produce opposite effects on strength, moisture sensitivity, and thermal conductivity [33].

3.6. Raw-material selection criteria

The evaluation of raw materials for high-pressure-formed bricks should consider particle-size distribution, plasticity, mineralogical composition, chemical composition, moisture demand, density, and reactivity [34]. For waste-derived materials, additional assessments are necessary for soluble salts, sulfates, chlorides, fluorides, heavy metals, loss on ignition, and leaching behavior [35].

High-pressure forming facilitates the use of diverse natural and secondary raw materials. However, pressing pressure alone does not mitigate issues such as improper grading, excessive water

demand, unstable compounds, or hazardous constituents. Effective production requires the coordinated selection of raw materials, stabilizers, compaction parameters, and curing conditions.

4. Manufacturing technology and compaction parameters

The performance of high-pressure-formed bricks is determined by the entire production sequence, not solely by pressing pressure. Factors such as raw-material preparation, particle-size distribution, mixing procedure, forming moisture, pressure level, loading duration, demolding, and curing collectively influence packing density, pore structure, green strength, and the development of chemical bonds. Therefore, technological parameters must be selected as an integrated system and tailored to the mineralogical and physical properties of the raw materials.

4.1. Raw-material preparation and mixing

According to standards [36], [37], raw-material preparation typically involves drying, crushing, grinding, sieving, proportioning, and homogenization. Soil agglomerates and coarse waste particles must be reduced to a size appropriate for uniform filling of the mold. The particle-size distribution should include sufficient fine material to fill voids between larger particles. However, excessive grinding increases specific surface area, water demand, and the likelihood of powder agglomeration.

Waste-derived materials often require supplementary processing. For instance, recycled concrete may be crushed, ball-milled, sieved, and carbonated before use. Ouyang et al. [23] ground recycled concrete for four hours, passed the resulting powder through a 150-mesh sieve, and subjected it to accelerated carbonation for seven days. The liquid component was introduced in two stages, as single-step addition resulted in powder agglomeration and insufficiently uniform reactions.

Dry components are typically blended before the introduction of water, alkaline activators, or dissolved admixtures. The mixing sequence is especially critical for highly porous materials, as they can absorb a significant proportion of the added water before the water becomes uniformly distributed. In the production of coal-char-based bricks, water and superplasticizer were first mixed separately, while coal char and cement were dry-mixed before wet mixing (Figure 1). This staged mixing facilitated uniform water distribution throughout materials with high surface area and water-retention capacity [38].

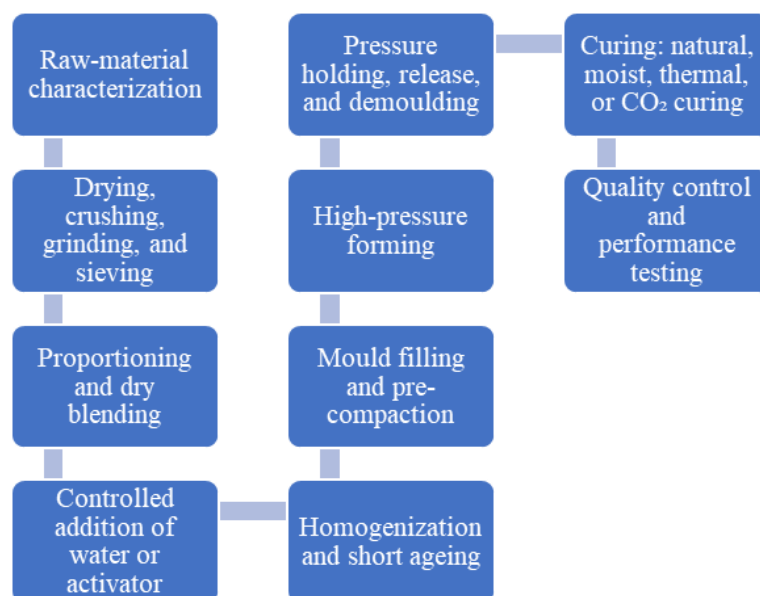


Figure 1 – General manufacturing route for high-pressure-formed bricks. Developed by the authors based on the manufacturing procedures reported in [23], [24], [36], [37], [38], [39], [40]

Although the general manufacturing sequence is similar, the relative importance of individual processing stages varies considerably across material categories. For CEBs and CSEBs, soil grading, optimum forming moisture, and moderate compaction are the key parameters, while subsequent strength development depends mainly on drying or cement/lime stabilization [19], [21], [25]. Cementitious high-pressure bricks rely more strongly on controlled low-moisture mixing, intensive compaction, and moist curing to promote cement hydration and pore refinement [22], [38], [40]. Alkali-activated pressed bricks require additional control of activator dosage, liquid-to-solid ratio, mixing sequence, and often thermal or steam curing to accelerate geopolymeric or alkali-activated reactions [23], [24]. In ultra-high-pressure waste-derived bricks, by contrast, very high compaction pressure itself becomes a major structure-forming factor, while subsequent natural, standard, or autoclave curing stabilizes the highly densified matrix [8], [9]. Therefore, the manufacturing route should not be treated as universal; the dominant control parameter shifts from soil moisture and grading to binder chemistry, activator conditions, or pressure-induced densification, depending on the material system. Particle size is especially important for porous organic additions and recycled materials. Coarse particles can disrupt mold filling and create local voids, whereas excessive grinding increases specific surface area and water demand. The particle-size distribution of sawdust and similar lightweight wastes should therefore be treated as an independent manufacturing parameter rather than merely a material characteristic. Mineralogical characterization is equally important for highly expansive clays, particularly montmorillonitic soils, because their moisture demand and response to stabilizers differ substantially from those of less active clays [41], [42].

4.2. Moisture content during forming

The moisture content during forming governs both the fresh mixture cohesion and efficiency of compaction. Insufficient moisture leads to the formation of only a limited number of liquid bridges between particles, resulting in poor cohesion, incomplete mold filling, weak edges, and potential delamination during demolding. In contrast, excessive water separates particles, increases pore-water pressure, and may cause slurry extrusion, drying shrinkage, and reduced mechanical strength.

The optimum moisture content is specific to each raw material system. For the clay studied by Schiavo et al. [43], dry pressing was effective above the pendular-to-funicular moisture transition at approximately 5.7 wt.%. The workability range for plastic forming was observed at approximately 15–18 wt.%, where particle packing reached a maximum before transitioning to a water-saturated capillary state. Although these values are not universal, they illustrate that successful forming occurs within a narrow moisture range.

A comparable optimum moisture range has been identified in waste-based alkali-activated bricks. When the water-to-solid ratio was below 0.15, insufficient bonding and limited water availability impeded both the formation and subsequent chemical reactions. Ratios above 0.25 resulted in excess liquid escaping from the mold during pressing and increased porosity following evaporation. A ratio of approximately 0.20 achieved a more favorable balance among workability, compaction, and reaction development [24].

Highly porous constituents often require substantially more water than mineral powders. For example, coal-char-based bricks were produced at a water-to-cement ratio of 1.7 due to the char's high specific surface area and water-retention capacity. This finding indicates that moisture formation should not be determined exclusively by conventional cement-based mixture ranges [38].

For soil- and sludge-based mixtures, the optimum moisture content can be determined experimentally by identifying the maximum dry density achieved during compaction. In drinking-water-treatment-sludge bricks, increasing the sludge proportion reduced the optimum moisture content from 16% to 12%, demonstrating that the required water content can vary significantly even within the same general material system [39].

4.3. Pressing pressure and compaction mechanism

In the initial stage of pressing, particles rotate, slide, and rearrange, thereby eliminating large air voids. Continued loading deforms or fragments weak agglomerates, increasing both the number

and area of interparticle contacts. As pressure increases, the mixture approaches its maximum packing density, and subsequent increases in pressure yield diminishing improvements.

The required compaction pressure varies significantly across material systems. Cement-based lightweight bricks are typically produced at approximately 3–10 MPa, whereas alkali-activated pressed bricks, including geopolymer systems, have been studied at pressures ranging from 0 to 60 MPa. Hyper-compacted earth bricks are formed at around 100 MPa, and ultra-high-pressure waste-derived bricks are manufactured at 100–400 MPa. These values do not represent a universal classification, as the necessary pressure depends on factors such as particle stiffness, moisture content, binder type, mold geometry, and the target product density [13], [24], [38].

In clay-fly-ash geopolymer systems, increasing the molding pressure enhances precursor wettability, reduces porosity and water absorption, and increases both bulk density and compressive strength. Pressing is particularly advantageous for semi-dry geopolymer mixtures, as mechanical contact partially compensates for their low liquid-to-solid ratio and facilitates interaction between the alkaline solution and aluminosilicate particles [24].

However, the relationship between applied pressure and material performance is not always linear. For bricks produced entirely from calcium carbide slag, the optimal pressure is approximately 200 MPa. Beyond this threshold, further increases in pressure result in minimal additional reduction in internal porosity. Excessive loading can also induce particle crushing, elastic recovery, density gradients, or microcracking following pressure release [9].

A comparable threshold was identified for aluminum-ash-calcium-carbide-slag bricks. Pressures ranging from 100 to 400 MPa were examined, with the optimal value determined to be approximately 300 MPa. At an aluminum ash-to-carbide slag ratio of 1:9 and after five days of natural curing, these bricks achieved a compressive strength of approximately 75 MPa and a softening coefficient of about 0.99 [8].

4.4. Loading regime, holding time, and demolding

Beyond maximum pressure, factors such as loading rate, holding duration, mold filling method, and pressure-release procedure affect the uniformity of the compact. A brief holding period facilitates particle rearrangement and water redistribution. However, excessively long cycles may reduce industrial productivity without a corresponding increase in density.

Reported holding times typically range from one to two minutes. For example, coal-char mixtures were pressed for one minute at 3.5–10 MPa, while drinking-water-treatment-sludge mixtures were held under load for two minutes. Semi-dry geopolymer specimens could be demolded immediately after pressing, as particle compaction generated sufficient green strength [24], [38], [39].

Uniaxial pressing is the most widely used laboratory method. However, friction between the mixture and mold walls can result in density gradients across the brick thickness. In industrial production, double-sided pressing can mitigate this effect. Gradual unloading is preferable, as rapid pressure release may induce elastic springback, lamination, or cracking, especially in dry mixtures and products formed at ultra-high pressure.

4.5. Curing conditions

Following demolding, the compacted structure requires stabilization through processes such as drying, hydration, pozzolanic reactions, geopolymerisation, carbonation, or their combinations. Reported curing methods for high-pressure-formed bricks include natural, moist, standard, water immersion, thermal, steam or autoclave, and accelerated CO₂ curing.

For bricks containing cement, maintaining adequate humidity during the initial curing period is essential. Coal-char bricks cured at 40 °C showed accelerated early strength development; however, the highest 28-day strength was achieved at 20 °C and 90% relative humidity. Exposure to 40–60 °C with only 15% relative humidity caused rapid moisture loss and limited the hydration of unreacted cement [38].

Thermal curing reduces the production cycle of alkali-activated bricks. Ouyang et al. [23] applied steam curing at 60 °C for nine hours to pressed recycled-concrete-fine-slag bricks, followed

by 24 hours of standard curing at 20 ± 2 °C and relative humidity above 95%. This combined approach accelerated initial reactions and enabled subsequent moisture-controlled hardening.

The optimal curing regime is highly dependent on the chemistry of the raw materials. Aluminum-ash-calcium-carbide-slag bricks performed best after approximately five days of natural curing, while calcium-carbide-slag bricks responded more favorably to standard and autoclave curing. For the latter, optimal conditions included a moisture content of 15%, pressure of 200 MPa, and a curing duration of three days [9].

Specialized curing regimes can address the challenges posed by highly water-absorbing wastes. Early immersion of pressed bricks containing drinking-water-treatment sludge for three days, followed by standard curing, provided sufficient water for hydration and mitigated the negative effects of organic components. Under this two-stage curing regime, the B60 mixture containing 60% drinking-water-treatment sludge achieved a 28-day compressive strength of 16.2 ± 1.7 MPa [39].

Accelerated carbonation serves as an additional curing method for calcium-rich waste-based bricks. In cement-kiln-dust-brick-waste systems, alkaline cement kiln dust activates silica- and alumina-containing phases, while CO₂ curing facilitates the simultaneous formation of C–S–H and CaCO₃. Incorporating silica fume further reduces the Ca/Si ratio of C–S–H and enhances its binding capacity. Bricks with silica fume met the requirements for severe-weathering masonry units under both air and water curing, indicating that both curing medium and reactive-filler content require joint optimization [44].

4.6. Industrial production and process control

Scaling up from laboratory specimens to full-sized bricks necessitates precise control of mixture mass, moisture distribution, mold filling, pressing energy, density uniformity, and curing conditions. Discrepancies between laboratory and industrial results often arise due to variations in mixer efficiency, mold geometry, pressure transmission, specimen dimensions, and testing procedures.

Oti et al. [40] demonstrated the production of full-sized unfired clay bricks using an industrial hydraulic press. Each brick was formed from a constant mass of approximately 2.6 kg and moist-cured at approximately 20 °C. The authors observed that direct comparison between laboratory and industrial bricks is challenging due to differences in brick shapes, binder contents, mixing procedures, and compaction methods across scales.

For industrial implementation, process control should include continuous monitoring of raw-material moisture, particle grading, mixture mass, peak pressure, holding time, green density, and dimensional accuracy. Pressing pressure should be optimized based on required performance criteria, as exceeding the densification threshold increases energy consumption and equipment wear without significant technical benefit. Manufacturing parameters of high-pressure-formed bricks are demonstrated in Table 3.

Table 3 – Representative manufacturing parameters reported for high-pressure-formed bricks

Material system	Forming moisture	Pressure/loading	Holding or demolding	Curing regime
Coal-char-cement bricks	High water demand; W/C = 1.7	3.5, 7 and 10 MPa	1 min	20–60 °C; 15–90% relative humidity
Clay-fly-ash geopolymer bricks	Semi-dry; liquid/solid = 0.25	0–60 MPa	Immediate demolding	Low-temperature thermal curing
Aluminum ash–carbide slag bricks	Initial waste moisture controlled	100–400 MPa; optimum $\approx$ 300 MPa	Not consistently reported	Natural curing, optimum $\approx$ 5 days
Calcium-carbide-slag bricks	Optimum $\approx$ 15%	100–400 MPa; optimum $\approx$ 200 MPa	Demolded after pressing	Natural, standard, water and autoclave curing
Carbonated recycled-fine-slag bricks	w/s = 0.15–0.25; optimum $\approx$ 0.20	Constant molding load	After compaction	60 °C steam for 9 h + standard curing

Note: applied loads and pressures cannot be compared directly without considering the loaded mold area and specimen dimensions. The representative manufacturing parameters were compiled from the following experimental studies: coal-char-cement bricks [38]; clay-fly-ash geopolymers bricks [24]; aluminum ash-calcium carbide slag bricks [8]; calcium carbide slag bricks [9]; and carbonated recycled-concrete-fine-slag bricks [23].

5. Structure formation and properties

High-pressure-formed bricks derive their properties from two main mechanisms: mechanical densification during pressing and physical or chemical bonding during curing [45]. Compaction of bricks reduces voids and increases particle contact, while hydration, pozzolanic reactions, alkali activation, or carbonation further strengthen these bonds [46]. The influence of each mechanism depends on raw material composition, binder system, moisture content, pressure, and curing conditions.

5.1. Structure-formation mechanisms

In cement- and lime-stabilized systems, structure formation primarily results from the production of calcium silicate hydrate (C–S–H), calcium aluminosilicate hydrate (C–A–S–H), and ettringite. These compounds bind soil or waste particles and fill pore spaces. Tao et al. [47] found that combining cement, GGBS, quicklime, and gypsum produced a denser matrix than cement alone, as GGBS improved particle packing and contributed to secondary reactions. However, too much gypsum led to excess ettringite, causing internal expansion and reduced strength.

Reactive additives can further improve the binder matrix. Liu and Fan demonstrated that sodium silicate activates calcium- and silica-containing phases, while microsilica consumes calcium hydroxide and promotes a denser, fibrous C–S–H-rich structure [48]. At optimal additive levels, the cross-linked gel connects coarse particles and reduces weak zones. Wood fibers also help limit the initiation and spread of microcracks.

In ultra-high-pressure waste-derived bricks, densification is as important as chemical bonding. Ren et al. [8] produced dense bricks from aluminum ash and calcium carbide slag without using a conventional cement binder. The strength was due to close particle contact, deformation of weak agglomerates, reduced porosity, and limited reactions between calcium- and alumina-containing phases during curing.

The efficiency of slag-based stabilization depends largely on the activator. Oti et al. [40] found that lime-activated GGBS produced higher compressive strength than Portland-cement-activated GGBS in unfired clay bricks. Scanning electron microscopy and energy-dispersive X-ray spectroscopy analyses linked this to faster slag hydration and greater formation of C–S–H and additional pozzolanic gel around clay particles. GGBS also reduced large capillary pores and limited the formation of disruptive ettringite by creating a finer, more stable matrix [40]. Granulation is another way to improve contact between reactive fine particles. Fly-ash-lime granules retain moisture within agglomerates and increase interparticle contact, which accelerates pozzolanic reactions. After hydrothermal treatment, the formation of C–S–H, calcium aluminosilicate hydrates, and Al-substituted tobermorite resulted in compressive strengths of about 47.0–62.5 MPa and helped retain Cd, Ni, Pb, and Zn in the brick matrix [49].

5.2. Pore structure, density, and water absorption

Pore connectivity is more important than total porosity alone. A structure with small, isolated pores can maintain satisfactory durability, whereas connected capillary pores facilitate water penetration and freeze-thaw damage. Appropriate pressure and moisture reduce open porosity, but insufficient water limits compaction and hydration, while excess water leaves interconnected pores after drying [50].

Sun identified a liquid-to-solid ratio of 17% as optimal for construction and demolition waste (CDW)-based bricks compacted at 20 MPa. The resulting material exhibited a dense and homogeneous microstructure, a 28-day compressive strength of 17.54 MPa, water absorption of

7.41%, and a freeze-thaw strength loss of 7.75%. Lower liquid-to-solid ratios led to poor cohesion and particle loss, while higher ratios caused bleeding and drying cracks, thereby increasing pore connectivity [51].

The incorporation of GGBS and other fine reactive materials improves particle grading and fills pores with hydration products. In sandy-soil bricks, the optimal cement-GGBS-lime-gypsum system reduced water absorption to approximately 2.5% after 28 days, in contrast to significantly higher values observed in bricks stabilized with cement alone. However, excessive gypsum negated this improvement, as the formation of expansive ettringite promoted microcracking [47].

5.3. Mechanical properties

Compressive strength typically increases with greater density, binder reactivity, and extended curing time. However, high density alone does not guarantee high strength if the compact exhibits lamination cracks, weak interfaces, or uneven water distribution. Comparisons between studies should be approached with caution, as specimen dimensions, loading direction, moisture condition, and testing method significantly influence measured strength.

The mechanical response of earth-based bricks is highly sensitive to specimen geometry and confinement conditions. Low-height specimens can yield artificially elevated compressive strength values due to platen friction restricting lateral deformation. Consequently, strength data should be accompanied by detailed reporting of specimen dimensions, aspect ratio, moisture condition, loading direction, and loading rate. Correction factors established for concrete or fired masonry are not directly applicable to unfired earth bricks [52].

Waste-based bricks can achieve a significant portion of their final strength at an early age when adequate cementitious reactions occur. Xiong et al. [53] found that most excavated-soil-fine-recycled-concrete-aggregate bricks attained approximately 80% of their 28-day strength within seven days, with a maximum 28-day compressive strength of 16.05 MPa. These findings indicate that water-to-cement ratio, cement-to-soil ratio, recycled-aggregate content, and compound-additive dosage should be evaluated collectively rather than in isolation.

A comparable balance between strength and durability was observed in unfired bricks produced from high-water-content slurry. For a different high-water-content slurry system, an optimized binder containing 10% desulfurized gypsum, 10% MgO, and 15% GGBS achieved a 28-day unconfined compressive strength of 16.2 MPa and a water-stability coefficient of 0.86 [54].

5.4. Water resistance and durability

Water resistance is typically assessed through water absorption, softening coefficient, wetting-drying cycles, and freeze-thaw testing. Durability increases when hydration products refine pore structure and when fibers or other reinforcements limit crack propagation. In contrast, open pores and weak particle-binder interfaces promote saturation, swelling, and surface deterioration.

Liu and Fan [48] reported that incorporating 0.1% wood fiber reduced the freeze-thaw strength loss of CDW-based bricks to 5.6%, which was 39% lower than that of the fiber-free control mixture. Fiber contents above 0.1% were less effective because inadequate dispersion promoted fiber agglomeration, weak interfaces, and microcracking during freezing. In a separate study, Sun [51] showed that the mixture with the optimum liquid-to-solid ratio maintained its integrity after 15 freeze-thaw cycles, whereas mixtures with insufficient or excessive liquid exhibited spalling, delamination, or disintegration.

Laboratory durability indicators do not always accurately reflect service performance. Seco et al. [30] determined that total water absorption correlates more strongly with outdoor durability than with capillary absorption. They also observed that certain standardized freeze-thaw procedures are either excessively severe or insufficiently representative of earth-based products. Therefore, durability assessment should integrate water uptake, retained strength, mass loss, visual damage, and realistic exposure conditions.

Freeze-thaw performance is influenced by both moisture condition and pore-size distribution. Oti et al. [40] reported no visible cracking, scaling, delamination, or fracture after 100 freeze-thaw

cycles in lime- or cement-activated GGBS clay bricks. Bruno et al. [55] found that dry freeze-thaw exposure did not diminish the mechanical performance of unfired earth bricks and could even enhance strength through continued densification or bonding. However, they emphasized that near-saturation must be avoided through appropriate architectural protection. These findings suggest that freeze-thaw resistance should always be evaluated in conjunction with water uptake and pore connectivity [56].

5.5. Thermal and moisture-related properties

Thermal conductivity is primarily influenced by density, pore structure, mineral composition, and moisture content. Increased compaction and cementitious bonding typically enhance conductivity by establishing more continuous solid heat-transfer pathways. Conversely, incorporating fibers and lightweight porous components reduces density and improves insulation, although these additions may also increase water absorption and decrease mechanical strength.

The addition of agricultural fibers can substantially decrease thermal conductivity. Ashour et al. [52] demonstrated that increasing the content of wheat or barley straw reduced the thermal conductivity of unfired earth bricks, whereas higher proportions of cement and gypsum increased it. Therefore, an optimal balance must be achieved between mechanical performance and thermal insulation.

Unfired clay bricks exhibit a relatively high moisture-buffering capacity. El Fgaier et al. [57] reported an equilibrium moisture content of approximately 3.5% at 95% relative humidity. While moisture adsorption can help regulate indoor humidity, it simultaneously reduces both compressive strength and thermal resistance. Consequently, thermal properties should be measured or adjusted at moisture conditions representative of actual service environments, rather than exclusively in a completely dry state. The thermal conductivity of unfired bricks increases with both density and moisture content. Oti et al. [40] observed an approximately linear increase in conductivity with increasing brick density, while El Fgaier et al. [57] found an increase of about 20% when relative humidity rose from 40% to 95%. This increase in moisture also reduced compressive strength by more than 50% in two of the investigated brick types. These findings confirm that thermal values measured only under oven-dry conditions may overestimate in-service thermal resistance. These structure-property relationships (spanning pressure, moisture, binder chemistry, and reinforcement effects) are summarized in Table 4.

Table 4 – Principal structure–property relationships in high-pressure-formed bricks

Controlling factor	Microstructural effect	Resulting properties
Increasing pressure to the optimum level	Particle rearrangement, reduced large pores, increased contact area	Higher density and strength; lower water absorption
Pressure above the effective densification threshold	Particle crushing, elastic recovery, lamination or microcracking	Limited strength gain and possible durability reduction
Optimum forming moisture	Improved lubrication, packing, and binder hydration	Dense structure, stable demolding, higher strength
Excess forming water	Bleeding and interconnected pores after drying	Higher absorption and lower frost resistance
Cement, lime, or activated GGBS	Formation of C–S–H, C–A–S–H, and related products	Increased strength and water resistance
Controlled gypsum addition	Accelerated reactions and ettringite formation	Improved early strength and pore filling
Excess gypsum	Expansive ettringite and internal stresses	Cracking and strength reduction
Microsilica or reactive fine waste	Filler action and secondary formation of C–S–H	Refined pores and stronger particle bonding
Low fiber content	Crack bridging and stress redistribution	Improved flexural and freeze-thaw performance
High fiber or organic-waste content	Agglomeration and increased porosity	Lower density and thermal conductivity, but possible strength loss

Note: the effects of increasing compaction pressure and the existence of an effective densification threshold were summarized from studies on geopolymer and ultra-high-pressure waste-derived bricks [8], [9], [24]; the influence of optimum and excessive forming moisture was based on dry-pressing and CDW-brick studies [43], [51]; the effects of cement-, lime-, and GGBS-based stabilization were summarized from studies of stabilized soil and unfired clay bricks [40], [47]; the beneficial and adverse effects of controlled and excessive gypsum addition were based on Tao et al. [47]; the filler and secondary-reaction effects of microsilica and other reactive fines were based on Liu and Fan [48]; the influence of low fiber contents on crack control and freeze-thaw performance was based on Liu and Fan [48]; and the effects of excessive fiber or organic-waste contents on porosity, density, thermal conductivity, and strength were summarized from studies of wood-fiber- and agricultural-waste-containing bricks [42], [48], [52].

Research on pressed and subsequently fired bricks offers valuable comparative data; however, these findings should not be directly applied to unfired systems. In fired products, compressive strength and water absorption are primarily determined by mineral transformations, sintering processes, heating rates, and the evolution of the pore network. The presence of carbonate and clay minerals can facilitate the formation of robust high-temperature phases, while organic wastes and concrete residues typically increase porosity following burnout. These mechanisms are fundamentally distinct from the hydration- and compaction-driven structure formation observed in unfired bricks [58], [59], [60], [61].

6. Environmental and practical considerations

High-pressure-formed unfired bricks can reduce several environmental burdens associated with conventional fired-clay brick production by eliminating kiln firing and reducing demand for virgin clay. Global fired-clay brick production is associated with substantial energy consumption and greenhouse-gas emissions [62]. In addition, extracting clay-rich topsoil for brick manufacturing can degrade agricultural land and reduce crop productivity [63].

However, the absence of firing does not automatically guarantee low environmental impact. A cradle-to-gate life-cycle assessment reported that unfired bricks generated approximately 29% lower CO₂ emissions than fired bricks, while cement production and transportation remained major contributors to the environmental footprint [64]. Therefore, the environmental performance of high-pressure-formed bricks depends strongly on binder content, transport distance, electricity use, and the extent of raw-material pretreatment.

Waste-derived bricks also require an environmental safety assessment when industrial or mining residues contain potentially hazardous constituents. Wang et al. [65] demonstrated that hydration products and a dense pore structure can substantially reduce heavy-metal mobility in unfired bricks containing mine tailings and municipal solid waste incineration fly ash. Nevertheless, appropriate leaching tests are necessary to verify the long-term stability of immobilized contaminants under relevant exposure conditions [65].

From a practical perspective, high-pressure forming offers precise geometry, relatively short production cycles, and the possibility of locating production near sources of secondary raw materials. Industrial implementation, however, requires consistent raw-material quality, controlled moisture and curing conditions, reliable pressing equipment, and compliance with mechanical, durability, and environmental requirements. The greatest environmental benefit is expected when locally available wastes and low-carbon binders are used, Portland cement consumption is minimized, and pressing pressure is limited to the level required to achieve the target performance.

7. Discussion and future research

The reviewed literature confirms that high-pressure-formed bricks cannot be evaluated as a single material category. Similar terms are used for soil-based blocks, cementitious products, alkali-activated systems, and ultra-high-pressure waste-derived bricks, although their compositions and hardening mechanisms differ substantially. Direct comparison is further complicated by variations in specimen dimensions, moisture condition, pressing regime, curing method, loading direction, and

testing standards. Future publications should therefore report the full set of production parameters and avoid using compressive strength as the sole performance criterion [2], [15], [66].

The available results also demonstrate several performance trade-offs. Increasing compaction pressure and binder content generally improves strength and water resistance, but may increase production energy, thermal conductivity, and embodied carbon. Conversely, porous wastes and plant fibers may improve thermal insulation while increasing water demand and reducing mechanical performance. Waste-derived bricks also require long-term leaching assessment because cracking, carbonation, or repeated wetting may alter contaminant mobility. Environmental advantages should therefore be demonstrated through combined mechanical, durability, leaching, and life-cycle assessments rather than inferred only from the absence of firing or the percentage of waste incorporated [30], [64], [65].

Future research should focus on standardized pressure ranges and reporting procedures, realistic wetting-drying and freeze-thaw exposure, dimensional stability, efflorescence, thermal performance under variable humidity, and compatibility with masonry mortars. Laboratory mixtures should also be validated using full-sized bricks and industrial presses. Particular attention is required to locally available low-carbon binders, the pretreatment of hazardous waste, reuse or recycling at the end of service life, and combined life-cycle and economic assessment. Data-driven mixture optimization may help identify compositions that balance strength, durability, insulation, environmental safety, and production cost rather than maximizing a single property. These priorities are important because the environmental benefit of high-pressure-formed bricks ultimately depends on local raw materials, transport distances, energy sources, and intended exposure conditions [2], [54], [62].

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Information about authors:

Ruslan Nurlybayev – PhD, Director, "Technopark Stroytech" Scientific Research Laboratory of Construction and Building Materials, Satbayev University, Almaty, Republic of Kazakhstan, rusya_nre@mail.ru

Maratbek Zhuginissov – Doctor of Technical Sciences, Professor, Bassenov Institute of Architecture and Civil Engineering, Satbayev University, Almaty, Republic of Kazakhstan, m.zhuginissov@satbayev.university

Yelzhan Orynbekov – Candidate of Technical Sciences, Researcher, "Technopark Stroytech" Scientific Research Laboratory of Construction and Building Materials, Satbayev University, Almaty, Republic of Kazakhstan, eljan_79@mail.ru

Yerlan Khamza – PhD, Engineer, "Technopark Stroytech" Scientific Research Laboratory of Construction and Building Materials, Satbayev University, Almaty, Republic of Kazakhstan, y.khamza@satbayev.university

Yerlan Kushekov – PhD Student, Engineer, "Technopark Stroytech" Scientific Research Laboratory of Construction and Building Materials, Satbayev University, Almaty, Republic of Kazakhstan, kush_er@mail.ru

Author Contributions:

Ruslan Nurlybayev – conceptualization, methodology, resources, supervision, interpretation, review and editing, funding acquisition.

Maratbek Zhuginissov – conceptualization, methodology, validation, interpretation, supervision, review and editing.

Yelzhan Orynbekov – literature search, data collection, data curation, formal analysis, visualization, writing – original draft.

Yerlan Khamza – methodology, data collection, formal analysis, interpretation, visualization, writing – original draft, review and editing.

Yerlan Kushekov – literature search, data collection, data curation, visualization, writing – original draft, review and editing.

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