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PERLITE: CHARACTERIZATION, MODIFICATION AND APPLICATIONS

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Abstract

Perlite is a glass-like amorphous (non-crystalline) mineral created by nature. Its composition is made up of high amounts, mainly, pertaining to silicon oxide (SiO_2) and aluminum oxide (Al_2O_3), coupled with a trivial amount of alkali metal oxides (Na_2O and K_2O, respectively) as well as other elements. It is produced by the rapid cooling of volcanic stone (obsidian), therefore, when heated, it undergoes expansion, which in turn is responsible for its lightweight and porous nature, making it a remarkable and versatile material with various applications. Presently, the broad horizon of uses, include but not limited to, construction and cryogenic insulation, thanks to its exceptional thermal characteristics; filtration and horticulture, due to its porous nature; as a fireproofing agent on account of it being non-combustible; even in various drug delivery systems as a carrier, in the preparation of catalysts, as a filler, aggregate for light cement etc. Another interesting use of perlite is in the production of cosmetics, where it is used as a gentle exfoliant in skincare products. In addition, perlite is a major constituent in ceramic production, as it effectively aids in reducing and preventing cracking/shrinkage during firing due to its ability to absorb water and expand, thus reducing stress within the ceramic, which in turn leads to improved overall quality of the finished pieces/products; as well as, the purifying of solutions by adsorbing heavy metals, attributed to it being a permeable and inert material, are noteworthy mentions. Consequently, through meticulous review, this paper provides an in-depth analysis of the modifications of perlite, the comparison of physical-chemical and mineralogical characteristics of both natural resources, and summarizes the utilization status of perlite.

Keywords: perlite, modifications, characterization, applications

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1. Introduction

Within the category of pyroclastic rocks (also referred to as volcanic or extrusive igneous rocks), which form when molten rock (magma or lava) erupts and cools rapidly at or near the Earth's surface (typically around volcanic vents or fissures), there exists a notable subclass known as ***rhyolite***. One particular variety, often termed "*glassy rhyolite*," is composed primarily of silicon dioxide, aluminum oxide, oxygen, and structurally bound water, often in hexagonal or molecular form [1–3].

The term "*perlite*" does not have a single, universal definition; its meaning can vary significantly depending on the context (be it petrographic, industrial, or chemical). Each perspective offers unique insight into its characteristics and applications.

From a **petrographic** standpoint, *perlite* is not a commercial label but rather a general term used to describe naturally occurring, hydrated, silica-rich volcanic rocks that belong to the rhyolite group. These rocks are formed as a result of volcanic activity and are characterized by their high silica content and often glassy appearance.

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Industrially, *perlite* is defined as a hydrated felsic rock (also referred to as an "altered silicic rock" or "micro-felsitic" rock). These terms imply a volcanic rock that has undergone alteration, possibly through weathering, hydrothermal processes, or devitrification, resulting in partial crystal formation without full crystallization. When rapidly heated, this rock expands dramatically due to the vaporization of its internal water content, producing a lightweight, porous, white, sponge-like material. This thermal expansion is central to its value in industrial applications such as insulation, filtration, and lightweight aggregates.

Chemically, *perlite* is described as a metastable, non-crystalline (amorphous or cryptocrystalline) aluminum silicate. Its texture can also be tuffaceous (a rock formed from volcanic ash).

This definition underscores the dominance of SiO_2 and Al_2O_3 in its composition, which contribute to its low density, high surface area, and chemical inertness.

From a **commercial perspective**, the term "*perlite*" encompasses both the raw volcanic glass and the expanded product obtained after thermal treatment. This dual nature is critical in understanding its lifecycle from extraction to application.

Recapitulating, these different definitions reflect the complex and interdisciplinary nature of perlite; bridging geology, materials science, and industrial processing.

While perlite falls in the "realm" of industrial minerals, it differs from classical minerals due to its variable elemental, chemical, and mineralogical composition, which may shift depending on the source and geological formation. This variability sets it apart from more compositionally consistent crystalline minerals [4–8].

2. Historical background, name origin, identification, "main modifications"

The mineral known as *perlite* has been recognized since at least the third century. However, the precise details of its initial discovery and historical usage have become somewhat obscured over time, leading to conflicting views on when it was commercially "re-discovered".

Its modern rediscovery is often linked to two separate "incidents" in the early 20th century. In 1914, an American dentist, while experimenting with tooth enamel, observed that certain volcanic materials expanded or "puffed" when subjected to high temperatures. Around the same time, a geologist working for a barite and silver mining company reported a similar phenomenon on the Greek island of Milos. During a coastal fire, beach sand (likely of volcanic origin) was thrown onto the flames and unexpectedly swelled, helping extinguish the fire. This curious reaction prompted further interest in the thermal behavior of volcanic glasses found abundantly across the Greek islands. So, the journey of "re-discovery" and processing of perlite started to gain momentum around the 1940s. By 1946, perlite had entered commercial production, marking the start of its industrial journey. Initial interest and growth in perlite processing were rapid, though expansion continued at a slower but steady rate in the following decades. By 1968, global mining volumes had reached approximately 558,000 tons [9–10].

According to Kadey Jr., F.L. (1983), the name "*perlite*" is believed to originate from the Old French word *perle*, meaning "*thé* pearl or pearl stone", a name first cited by Johannsen, A. in 1939. In the 19th century, German petrologists also used the equivalent term *Perlstein* to describe a type of glassy rhyolite or *hyaloliparite* that exhibited a pearly luster. This nomenclature may have been inspired by the elegant, pearl-like sheen of fractured perlite or by the small, rounded particles formed upon breaking, which resemble tiny pearls or the luminous glow that mirrors light, acting as a "carbon-copy" of the pearl gemstone, distinguishable to the naked eye or under a microscope [11–17].

Perlite was originally identified based on its distinctive glassy (vitreous), lustrous appearance, often described as "pearly", and its unique fracture pattern known as *perlitic fracture*. These fractures are typically concentric and curved, resembling the layered structure of an onion

("onion-skin"), which in turn, contributes to the rock's characteristic appearance and texture [8,14,18–20]. Perlite also exhibits a range of textures, which influence its commercial value and applications. These textures can be broadly classified into three main types; (a) classical/traditional perlite; (b) granular perlite; (c) pumiceous perlite [8,21].

Scientifically (or geologically), the word "*perlite*" alludes to ***hydrated volcanic glass***, emphasizing its unique composition and origin in volcanic environments. This definition encapsulates the essence of perlite as a mineral (or more precisely mineraloid, because unlike minerals, mineraloids are typically amorphous (non-crystalline)) with specific characteristics derived from volcanic processes [3,22]. The parent material (precursor) for perlite is volcanic glass (a state between crystalline solids and liquids) produced when rhyolitic lavas, rich in silica and low in evaporites, cool rapidly. This rapid cooling results in the formation of ***obsidian***, the most common volcanic glass, characterized by its smooth, black appearance and minimal crystal growth.

Over time, weathering causes very fine cracks to develop in the obsidian, allowing water to penetrate and deposit minerals such as quartz, cristobalite, and feldspar within these fissures. This gradual mineralization transforms the dense black obsidian into **perlite**, a porous volcanic rock often referred to as ***raw, crude, ore, "crushed" or unexpanded perlite***. Consequently, un-weathered obsidian frequently remains embedded within perlite deposits as black, white, or gray crystals, either as isolated grains or clusters, varying from plentiful to scarce depending on the perlite type [3,14,22-24].

When pre-sized raw perlite (***figure 1 (a)***) is rapidly heated within its softening temperature range of approximately 760–980°C (1400–1796°F), it undergoes a dramatic expansion or "popping" process. This thermal expansion forms numerous sealed, glassy cells (akin to how *popcorn* expands), resulting in a pyro-plastic transformation that converts raw perlite into ***expanded perlite*** (***figure 1 (c)***). This material is highly porous, lightweight, and frothy white, expanding to between **4 and 20 times its original volume** due to the vaporization of its inherent (indigenous) water content [8,11–14,22–34].

However, in industrial (commerce) terms, technically any volcanic glass that expands upon heating may be labeled as "perlite," including the raw material itself [5–6,22,29]. It is important to note that although the "true density" of perlite remains relatively not altered/constant (around 2.2–2.3 kg/L), its bulk density significantly decreases from about 70–120 g/L to 60–80 g/L after expansion. Moreover, thermal treatment induces structural changes, partially transforming the perlite from an **amorphous (non-crystalline**-non ordered structure**)** state toward a more **crystalline** (ordered structure) one. This process increases the number of fractured surfaces, enhancing the material's cation exchange capacity and doubling its specific surface area, from approximately 1.2 to 2.3 m^2/g [8,13,33–35].

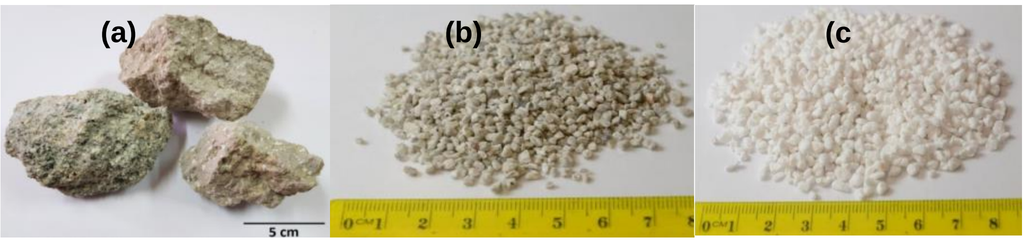


Figure 1. Perlite as seen **(a)** in a rock form collected from the Mariovo region, North Macedonia, **(b)** as an ore and **(c)** in expanded form, both supplied by the company Ausperl Pty Ltd.
(a) courtesy of Reka, *et al.*, (2019); and **(b), (c)** courtesy of Haery, H.A., (2017) [14,32].

3. Mineral-chemistry of perlite

Perlite is differentiated from other naturally occurring water-containing glasses like its precursor, “nebulous rock”, obsidian, expanded in Japan (less than 2 wt. % water), pitchstone, expanded in Eastern Europe (water content>4or>5 wt.%) or “*forth of the sea*”-hydrated volcanic ash-pumice/known as pumicite in its powdered form (16.3 wt. % when kept in the air, while, after soaking for 24 hours, the absorption increases to 50.8 wt. %) by its ***total water content of 2 to 5 wt.%*** enclosed within the glass structure [8,14,21,23,25,29-30,32-34,36-37].

The water in perlite comes from two sources: ***(a) primary (magmatic) water***: trapped during the formation of volcanic glass, typically around **0.1–0.5 wt.%**, present as **hydroxyl groups (OH^-)** chemically bonded within the silicate framework under hydrothermal conditions, and ***(b) secondary hydration (“additional” hydration)***: occurs after the rock cools, often through interaction with groundwater or meteoric water, contributing to structural/hexagonal water in molecular form (**H_2O**). The fluctuation in the amount of additional or "secondary" hydration water (0.1–5.0 wt. %) mirrors the differences in perlite texture, structure, and porosity. This hydration may occur under zeolitic facies or near-surface conditions [7,38-42].

Koukouzas, N., (1998); also noticed with **Transmission Infrared spectroscopy (IR)**, as seen in ***figure 2***, that two main water peaks are detectable in perlite (from the island of Kimolos, Greece). The initial one is a symmetrical band at around 1630 cm^{-1}, linked to lattice or coordinated water, while the second is a wide asymmetric band at about 3570 cm^{-1}, associated with OH-bound molecular water [43-44].

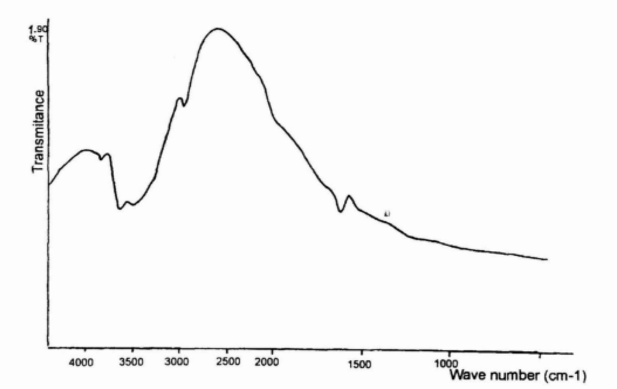


Figure 2. IR of perlite from the island of Kimolos, Greece, showing the symmetrical band that represents coordinated water and the asymmetrical band that belongs to molecular water [43].

Perlite consists predominantly of major oxides: SiO_2, Al_2O_3, K_2O, Na_2O; minor constituents: TiO_2, CaO, MgO, Fe_2O_3, water, and small amounts of unburned carbon [45]. Because of its high silica and alumina content, especially in its finely ground form, perlite exhibits pozzolanic activity (the capacity to chemically react with calcium hydroxide in the presence of moisture, forming cementitious compounds). This property is attributed to its amorphous (non-crystalline) glassy structure [3,46].

X-ray powder diffraction (XRPD) is commonly used to identify perlite’s mineral phases. While crystalline inclusions produce sharp peaks, the amorphous matrix appears as a broad hump or “bulge” (15–35° 2θ) on the diffractogram, characteristic of non-crystalline silicates. This hump reflects the glassy groundmass of perlite [5,14,23,32,47].

Although perlite is largely amorphous, **crude perlite** often contains crystalline inclusions such as:

- **Quartz, cristobalite, and feldspars** (albite, orthoclase, microcline)
- Potentially (hypothetically): **biotite, anorthite, ilmenite, and chlorapatite** [14,23,31,48–49].

Crystallinity varies in intensity, with feldspars typically showing the strongest diffraction peaks, followed by quartz and cristobalite; and the weakest peaks appear from cristobalite.

It's important to note that inclusions like mica, hematite, magnetite, ilmenite, zircon, and spinel have also been stated in different bibliographies as mineral phases of perlite. However, these *non-expandable* phases are considered unwanted (impurities) as they can lead to fragmentation during the expansion process, resulting in the production of un-desired ultra-fines.

Studies have shown that expanded perlite remains predominantly amorphous [32,47,50-51]. The expansion process affects only the amorphous phase; crystallites remain unexpanded and are often discarded.

The chemical composition between raw and expanded perlite is similar, although expanded perlite contains less bound water, highlighting hydration loss during heating. *This difference* in ***water content*** serves as a *crucial distinction between expanded perlite and its raw form*. Symbolically, ***Figure 3*** shows the typical diffractogram of native, as well as expanded perlite [14].

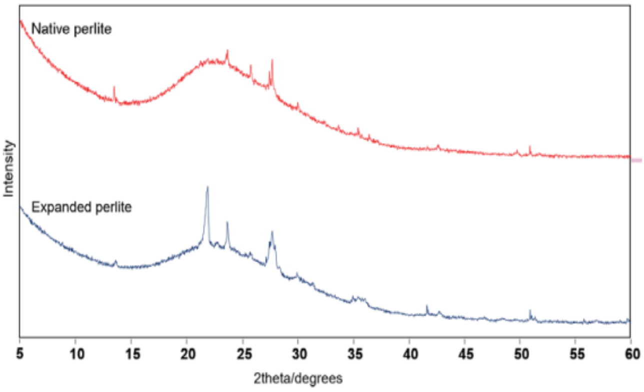


Figure 3. X-ray powder diffraction analysis (XRDP) of native/raw perlite (top) and expanded perlite (bottom), both from Mariovo region, North Macedonia, showing clearly the prevalence of amorphous phase in both materials; with a small quantity of crystalline phase in native/raw perlite. Adapted from Reka, *et al.*, (2019) (refer to citation [14] for detailed interpretation of the diffractogram) [14].

In view of the remarkable advantages that perlite utilization offers, the foundation stone of this article is reviewing the properties and the methods available for characterization that are of interest for both raw/crude/ore/unexpanded/“crushed” and expanded perlite.

At the same time, providing background information on perlite will enhance and facilitate understanding of its nature and properties and why it is considered "*an expanding mineral in a shrinking world*”, or to paraphrase, Dr. Harry Huntzicker that once stated, in an article that ran in the *Popular Mechanics* magazine, " *If we were to mix natural elements in a laboratory to create an ideal aggregate, the result would likely resemble perlite*". The article from Popular Mechanics magazine that was released in December 1954, likely provided valuable insights into the uses and properties of perlite, which has started from that time and continues to this day [referring to citation **52**].

Consequently, this review paper focuses on and highlights the latest research progress of perlite, showcasing its diverse and broad horizon of applications in construction, horticulture, industry, skincare products, with a special touch on ceramics and the purification of solutions by adsorbing heavy metals.

4. Summary of physico-chemical properties, classification, and hazard assessment of perlite

Physical properties

A standout feature of perlite is its foamy-like microstructure, which at the same time contributes to its low density of approximately 240 kg/m^3 [53-54]. Before expansion, perlite has a bulk density between 1.04 to 1.2 g/cm^3 (1104-1200 kg/m^3), while after expansion, de facto, expanded perlite, typically falls within the interval 0.032 to 0.4 g/cm^3 (30-150 kg/m^3) [14-15,23,31,55].

Despite the significant change in bulk density, "the true" density of perlite (refers to the density of perlite particles excluding the pore space within them. It is a measure of how much mass is packed into a given volume without considering the air or water content. This density for perlite, typically ranging from 1.1 to 1.3 g/cm^3) remains relatively stable and doesn't change significantly, due to the "escape" of combined water during the expansion process. This consistency in density is a result of the specific properties of perlite and the way it expands [3,56-57].

Expanded perlite can vary from fluffy, highly porous particles (89-95 vol% [32]) to glazed glassy particles with low porosity. The porosity of expanded perlite is advantageous for applications like drainage, aeration, moisture retention, and fertilizer in horticulture and landscaping. However, in thermal insulation applications, excess water absorption is unfavorable as it increases heat conductivity. The brilliant white color of expanded perlite, "gained" as a result of the expansion process, is beneficial in light-colored surface coatings. Color considerations are crucial in filler applications, particularly when the end product's color is a significant factor. The reflective white nature of perlite adds value in various applications where color plays a key role [8,32].

Perlite has a wide range of physical characteristics that make it a versatile mineral filler. Its expanded product has a density range of 32-400 kg/m^{3,} much lower than the crude ore's density range of 960-1200 kg/m^3, which in turn is lower than all the other minerals, for that matter.

Additionally, perlite has a specific gravity of 2.2-2.4 and a water retention capacity of 35-50%, which is relatively high compared to other minerals. The thermal conductivity of perlite is low, around 0.04-0.06 W/m°K at 24°C (75.2°F). Moreover, perlite exhibits a specific heat of 837 J/kg°K, a softening point between 871-1093°C (1599.8-1999.4°F), and a melting point ranging from 1260-1343°C (2300-2449.4°F). Its dielectric properties are given as 2.68+0.018i F/m and 2.72+0.011i F/m at frequencies between 1.5 GHz and 2.6 GHz, respectively [1,4,53].

Table 1. Some of the physical properties of perlites [2-3,5,14,17,23,58-59].

PROPERTY	CHARACTERISTICS/VALUE
Color	White to off white (expanded) Light grey/glossy black to brownish (raw)
General Electric Brightness	70-80% (78%)
Hardness Index (Mohs hardness)	5.5
Refractive Index	1.5 (1.47)
pH (water slurry)	6.5(7)–8.0
Non-floating	<5%
Free Moisture	Typical<1% (0.5%)
Specific Gravity	2.2–2.4
Apparent Density	40-170 (240) kg/m^3
Density	Expanded: 32-400 kg/m^3 Raw: 960-1200 kg/m^3

Bulk density (*loose*-weight)	Expanded: 0.032-0.4 g/cm^3 (30-150 kg/m^3) Raw: 1.04-1.2 g/cm^3 (1104-1200 kg/m^3)
Wet density (kg/m^3)	103 kg/m^3
Water Retention	35-50%
Oil Adsorption	50-100 grams of oil per gram of perlite
Softening Point	>850°C (871-1093°C) (1599.8-1999.4°F)
Melting Point ("fusion point")	1260-1343°C (2300-2449.4°F)
Specific Heat (nominal)	837 J/kg°K
Ignition Loss (3 h in 927°C or 1700.6°F)	1.5% maximum
Humidity	Up to 1.0% (0-0.5%)
Thermal Conductivity at 24°C	0.04–0.06 W/m°K
Maximum Strength	Up to 6.0 MPa
Porosity	70-85%
Portion of Air	80-95%
Mesh Size Available	4-8 mesh and finer
Calcination	<3%
Solubility	Dissolves in hot concentrated alkali and HF Somewhat (moderate) dissolvable (<10%) in 1N NaOH Slightly dissolvable (<3%) in mineral acids (1N) Very slightly dissolvable (<1%) in water or weak acids
Asbestos	Asbestos free
Combustibility	Non-combustible (fire protection class A1-does not contribute to fire at any stage, including a fully developed fire).

Chemical properties

Perlite (volcanic ash/glass), being a form of amorphous aluminosilicate, is chemically inert with a pH around 7, yet, it lacks buffering capacity and essential mineral nutrients [53,60]. It is a natural inorganic mineral, which makes it an environmentally friendly (ecological) "agent". It is a non-polluting material that does not dissolve in water, explode, or undergo chemical reactions. Additionally, perlite is free from radioactivity, consistent in quality, highly resistant to erosion, lightweight, and free of organic substances. These characteristics collectively make perlite a valuable and adaptable material in various applications [4,17,53,60-63].

Perlite not only contains the abovementioned chemical compounds (**refer to chapter 3**) but also trace amounts of various other elements, typically less than 2% by weight. These elements include: As, B, Be, Ba, Cl, Cr, Cu, Ga, Pb, La, Mn, Mo, Ni, Nb, Nd, S, Ti, Th, V, Y, Zr, and Zn.

These additional elements, even though present in trace amounts, contribute to the overall composition of perlite ores (*refer to ***table 2*** for detailed representation of elemental and chemical composition of perlites, including the elements that are in abundance as well as those that appear as trace elements*) [17,32,48,61-64].

Table 2. Typical elemental and chemical composition of perlites [14,17,23,59,65].

ELEMENT COMPOSITION, %		**CHEMICAL COMPOSITION, %**	
Silicon (Si)	33.8	Silicon dioxide (SiO_2)	72.08 (70-80%)

Aluminum (Al)	7.2	Alumina (Al_2O_3)	12.92 (12-16%)
Potassium (K)	3.5	Titanium dioxide (TiO_2)	0.90 (0-1%)
Sodium (Na)	3.4	Iron oxide (Fe_2O_3)	1.50 (0-1%)
Iron (Fe)	0.6	Magnesium oxide (MgO)	0.63 (0-1%)
Calcium (Ca)	0.6	Quick lime/calcium oxide (CaO)	0.88 (0-2%)
Magnesium (Mg)	0.2	Caustic soda/sodium oxide (Na_2O)	3.76 (2-5%)
Mica	0.2	Potassium oxide (K_2O)	4.33 (2-5%)
Oxygen (O)	47.5	Combined water (H_2O) *	<1%
Loss on Ignition (LoI) *	3-5%		

* Combined/chemical water (H_2O) less than 1% its attributed to expanded perlite, while loss on ignition (LoI) refers to raw perlite that usually has 3-5% combined/chemical water content [14,17,23,59-60,65].

Table 2, highlights the chemical composition of both raw perlite and expanded perlite, showing that silica (SiO_2) is the dominant component in both minerals at around 72.08% (70-80%). Additionally, Al_2O_3 is present at 12.92% (12-16%), while alkali metal oxides (K_2O and Na_2O) are at 4.33% and 3.76% (2-5%), respectively. These percentages suggest that perlite is well-suited for use in container glass. The presence of trace elements like TiO_2, Fe_2O_3, MgO, and CaO completes the composition.

The consistency in elemental/chemical composition between raw and expanded perlite is crucial because it shows that there are no significant changes in the elements found in both perlites, and for understanding the material's properties and potential applications [14,23,66].

Classification of perlite

Perlite is usually associated with rhyolite unless there's a specific combination of low silica and alkaline contents, in which case it can be classified as *dacitic*. This distinction is based on the mineral composition and characteristics of the perlite in different geological contexts (***Figure 4***) [2,5,67].

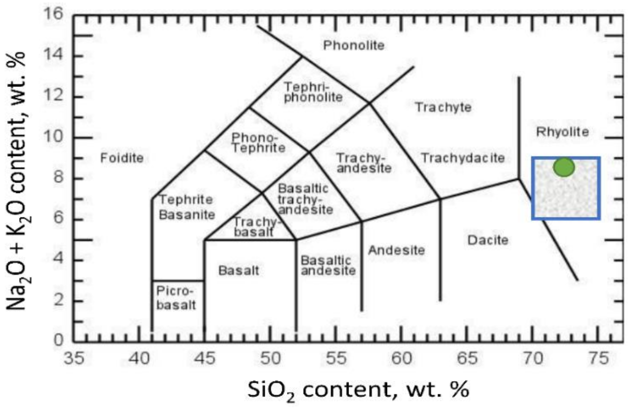


Figure 4. Illustration of the chemical classification of perlite using a TAS diagram (Total Alkali-Silica diagram) based on the typical chemical composition provided by the *Perlite Institute* (green circle) and the range suggested by Chatterjee, K.K., (2013); (blue rectangle) [2,5,67].

Perlites are typically classified based on *form*, *grade*, and *application*. The main classification categories help in organizing and understanding the different types of perlites available in the market. Each classification provides valuable information about the perlite's characteristics and best uses.

By form (main classification):

a) *Crushed/processed* (>3.4mm≈6.73 mesh size) is the equivalent of the perlite rock as it occurs in nature (raw/native);
b) *Expanded perlite* which can either be, milled (in powder form) with sizes varying between (-) 325 mesh (0.44 mm) to (-) 100 (0.149 mm) mesh, or in granule form; [2,67-70].

By grade:

It is determined by particle size. The classification includes *high*, *medium*, and *low-grade perlite*, which in turn depend on color, luster, and expansion values. High-grade perlite is jet black with a glassy luster and expansion values of more than 15 to 20 times. Medium-grade perlite is black with a dull luster and a mixture of rhyolitic material, with an expansion value ranging from 4 to 20 times. Low-grade perlite is black with vitrified, greyish patches and a mixture of rhyolitic material with an expansion value varying from 2 to 4 times [2,71].

By application:

- *Raw perlite rock* (finds applications amongst others, in slag granulation, special casting sand);
- *Milled expanded perlite* (finds applications in: filtration, as a cleaning absorbent, in horticulture and hydroponics (which is classified in *super-coarse*, *medium-coarse*, *coarse*, *fine*), as insecticide, as a building material, as portable ice box, as chemical container, as refractory material, in foundry, in boiler and pipe converting, as paint, as abrasive);
- *Expanded perlite granules* (which find applications as oil well drilling or in nuclear fuel elements) [2,67-70].

Hazard assessment of perlite

The perlite industry, supported by the *Perlite Institute* (a global trade group established in 1949) and various mining companies, has actively investigated the health impacts of natural and expanded perlite through collaborations with independent researchers and regulatory bodies. To date, research has consistently shown **no significant health risks** associated with perlite exposure during manufacturing, processing, or use [2,72].

Table 3. General information and material safety data sheet for perlite [73-75].

PRODUCT NAME	**PERLITE**
Chemical name	Sodium Potassium Aluminum Silicate
Chemical „family“	Silicate
„Formula“	Mixture
Apparence	White to off white/light grey/glossy black to brownish powder
Odor	Odorless
Solubility	Insoluble in water

Restriciton on use	Not applicable (n/a)
Classification	Not classified as hazardous (“nuisance dust”)
Safe storage	To uphold the integrity and quality of perlite, it's crucial to store it in a dry location. Additionally, it's important to ensure that perlite is not placed near hydrofluoric acid (HF) or strong basic solutions to prevent any potential reactions that could compromise its properties
Safe handling	Steering clear of getting perlite dust in the eyes Avoid inhaling the dust and handling any broken bags carefully by repairing them or disposing of them properly
Eye/Face protection	Google's, NIOSH/OSHA (National Institute for Occupational Safety and Health/Occupational Safety and Health Administration) tight tight-fitting safety glasses
Respiratory protection	Appropriate NIOSH/OSHA approved dust respirator when airborne dust exceeds the limitations given by OSHA PEL (Occupational Safety and Health Administration-Permissible Exposure Limit) and ACGIH TLV (American Conference of Governmental Industrial Hygienists-Threshold Limit Values)
Chemical „interactions“	Hydrofloric acid (HF), because on reaction it produces toxic silicon tetraflouride (SiF_4)
Symptoms	Inhaling perlite dust can lead to throat irritation, causing coughing and sneezing, and it might worsen any pre-existing respiratory conditions like bronchitis, emphysema, and asthma
Target organs	Eyes, lungs
Route of entry	Dust contact with particles, inhalation of said dust
Disposal	Perlite, on its own, is not considered hazardous waste and should be disposed of, following the relevant local, provincial, and federal regulations Proper disposal ensures environmental safety and compliance with waste management guidelines

According to OSHA (The Occupational Safety and Health Administration), perlite is classified as a **"Particulate Not Otherwise Regulated (PNOR)"**, with exposure limits comparable to those for nuisance or inert dusts.

Similarly, ACGIH (American Conference of Governmental Industrial Hygienists-Threshold Limit Value) classifies it as a **“nuisance dust.”** [74-76] However, perlite may contain trace amounts (<1%) of **crystalline silica (quartz)**, which is recognized as a **human carcinogen** by IARC (The International Agency for Research on Cancer) and NTP (National Toxicology Program). As such, **dust control measures** and **respiratory protection** are recommended in dusty environments to avoid prolonged inhalation.

Regulatory guidelines stress maintaining dust exposure below the Permissible Exposure Limits (PEL) based on an 8-hour workday. Despite the presence of crystalline silica, extensive animal and human studies have not linked perlite exposure to serious health effects, including pneumoconiosis. Overall, perlite is considered a low-risk material when handled according to occupational safety standards [2,11].

Table 4. Exposure limits related to perlite [74-77].

PERLITE	OSHA PEL **	ACGIH TLV **	MSHA PEL **	NIOSH REL **
Raw Perlite	15 mg/m^3 (total dust) 5 mg/m^3 (respirable dust)	10 mg/m^3 (total dust) 3 mg/m^3 (respirable dust)	10 mg/m^3	5 mg/m^3 (respirable dust) 10 mg/m^3 (total dust)
Expanded Perlite	15 mg/m^3 (total dust) 5 mg/m^3 (respirable dust)	10 mg/m^3 (total dust) 3 mg/m^3 (respirable dust)		5 mg/m^3 (respirable dust) 10 mg/m^3 (total dust)

*** It's important to note that exposure to perlite can result in temporary physical irritation, discomfort, impaired visibility, and an elevated risk of accidents for some workers. Recognizing these potential effects is vital for ensuring proper safety measures and protection in workplaces where perlite is handled [2,57].*

*** MSHA PEL-Mine Safety and Health Administration Permissible Exposure Limit.*

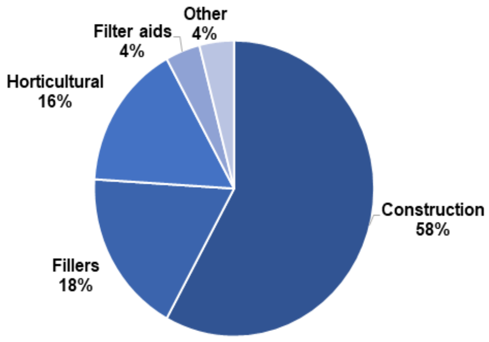
*** NIOSH REL-National Institute for Occupational Safety and Health Recommended Exposure Limit.*

5. Applications

The accidental discovery of perlite's expansion when exposed to high temperatures is a remarkable story. Back in 1939, Lee Boyer, while experimenting in his assay office in Superior, Arizona, aimed to create a new insulating material for the telephone industry by fusing silicates. One day, he tossed crushed perlite into a firebox, leading to a surprising outcome: lightweight mineral "nuggets" with a cellular structure ideal for heat resistance ("*that wonderful volcanic popcorn*"/*natures glassy marvel*). The "existence" of trapped ***water*** in natural perlite ore was crucial to this revelation. With assistance from the Arizona Department of Mineral Resources, the insulating and lightweight properties of expanded perlite were further explored. This led Boyer to start investigating various applications using expanded perlite [52,78].

Perlite, whether in its natural form or expanded, offers a wide diapason of applications due to its unique properties like: *low density, high porosity, chemical inertness, non-toxicity, relatively low price* and *excellent insulating capability* [14,16,23,32].

This versatile mineral can be divided into three general categories based on its application sectors: construction, horticulture, and industrial.



Graph 1. Graph showing the percentage of perlite use in different sectors [79].

Construction

Perlite plays a critical role in the construction industry, accounting for approximately 60–70% of its total global consumption [2,32]. Its standout properties, such as low density, thermal and acoustic insulation, fire resistance, chemical inertness, moisture resistance, and costeffectiveness, make it the “unsung hero” for uses in construction. Consequently, perlite is used across multiple sectors, including plaster, concrete, insulation, and ceiling tiles.

Portland cement-perlite plasters are widely applied as base layers and for fire protection of structural steel, offering durability and stability, while **gypsum-perlite plasters** provide lightweight, crack-resistant, and thermally efficient surfaces for walls and ceilings.

In **concrete**, expanded perlite serves as a lightweight aggregate, reducing thermal conductivity, structural weight, and improving insulation, though it may compromise compressive strength and homogeneity if not properly managed. **Perlite insulation** is applied as loose fill in masonry cavities, under floors, and in fire-resistant boards. It significantly reduces heat transfer and sound transmission and offers resistance to rot and corrosion, although its susceptibility to moisture can limit performance in damp environments. **Ceiling tiles** incorporating perlite benefit from enhanced fire resistance, thermal insulation, and sound absorption, but may require careful handling due to their fragility. Innovations like coating perlite with water-resistant substances or using latex binders improve its functionality in humid conditions. Overall, perlite remains a "silent performer" in construction, offering efficiency, safety, and sustainability in a broad range of building materials and applications [2,6,32,80-84].

Horticulture

Perlite is a highly beneficial material in horticulture, agriculture, and gardening, thanks to its unique physical and chemical properties. It improves soil structure by enhancing **aeration, drainage**, and **moisture retention**, holding up to **600% of its weight in water**, which it releases gradually to plant roots.

With a **neutral pH (6.5–7.5)**, it supports nutrient absorption without altering soil acidity. Its **porous, lightweight, and sterile** nature prevents soil compaction, promotes healthy root development, and minimizes issues like fungi and root rot, making it ideal for rooftop gardens, vertical farming, and hydroponic systems. Rich in **silica, iron, calcium, magnesium, and potassium**, perlite contributes to stronger plant growth and enhanced disease resistance. Its reflective surface improves light distribution to seedlings, and it can also be used as a **carrier for fertilizers, herbicides, and pesticides** or for **pelletizing seeds**.

Finely milled expanded perlite (typically ≤100 mesh) is especially effective for compost blending and hydroponics. However, a notable limitation is its tendency to **float to the soil surface**, particularly in containers, which may be unsuitable for certain plant types. Despite this, perlite remains a **versatile, sustainable, and cost-effective** soil amendment in modern cultivation practices [2,32,67,86-86].

Industrial applications

Perlite plays a significant role in various industrial sectors due to its unique properties such as low density, chemical inertness, porosity, and thermal insulation.

It is widely used in **cryogenic insulation**, where its low thermal conductivity, non-settling nature, and high porosity make it ideal for insulating tanks that store liquefied gases like oxygen, nitrogen at temperatures below –100°C (-148°F). Though effective, its moisture sensitivity and brittleness under mechanical stress are limitations.

In **filler applications**, expanded perlite (EP) enhances material performance by reducing weight, resisting shrinkage and cracking, improving machinability, and modifying surface texture. It exists in three forms: flakes, hollow microspheres, and lightweight bubbles, used in products like coatings, adhesives, polymers, and fire-rated doors. While perlite fillers are versatile, they can produce dust and have low compressive strength.

Figure 5. SEM images showing perlite as flakes, microspheres and bubbles [2].

As a **filter aid**, finely ground perlite is employed in the food, pharmaceutical, and beverage industries due to its inertness, porosity, and ability to trap fine particles without affecting taste or color. It is applied through pre-coating or body feeding techniques, though dust generation during use may require careful handling.

In **high-temperature applications**, such as steel and foundry operations, perlite functions in ladle and hot topping, risering, and mold cushioning by maintaining thermal insulation and enhancing metal quality. It is also used in refractory production, though its softening point (around 1100°C) limits its use at extremely high temperatures. Overall, perlite's diverse forms and thermal, chemical, and physical properties make it a critical industrial material, despite certain limitations requiring technical management [2,6,32,67,82,87-91].

Zeolite synthesis

Zeolites are fascinating minerals with unique properties due to their intricate structure. Their distinctiveness arises from the spatial aluminosilicate framework, which consists of interconnected tetrahedral units of [SiO_4] and [AlO_4] forming a polyhedral structure linked by all corners. This structure results in the formation of channels and cages with precisely defined molecular dimensions. These characteristics make zeolites valuable in various applications such as catalysis, adsorption, and ion exchange due to their porous nature and selective adsorption properties [32,92].

Numerous research studies have concentrated on synthesizing zeolites from affordable silica-alumina sources to establish cost-effective production techniques. This focus on synthetic zeolites underscores their importance in industrial applications where precise control over properties is crucial for optimal performance. Synthetic zeolites can indeed be "created" from different natural silica-alumina materials like acidic volcanic glasses, including natural and EP, and pumice.

The zeolitization of volcanic glass occurs *naturally* in a humid environment within a temperature range of 75-250°C (167-482°F), albeit it's a slow process.

In laboratory settings, researchers synthesize zeolites at temperatures below 200°C (392°F) using solutions like NaOH (sodium hydroxide) (or Na_2CO_3-sodium carbonate). This controlled synthesis approach enables the creation of zeolites with tailored properties and compositions suited for different applications. The ability to precisely control the synthesis conditions plays a crucial role in producing zeolites with specific characteristics to meet the demands of various industries [93].

Experimental studies have demonstrated that perlite, being a low-cost silica-alumina material, is a suitable resource for synthesizing various zeolites like: ZK-19, W, G, F, Na-Pc, HS, ZSM-5, A, V, Pc, Na-P1, P1, K-G, X, Y, analcime, solidate octahydrate, calcium zeolite, and many others [32,80,94-96].

Perlite in cosmetics

Perlite, being a natural and safe material, has various applications in cosmetics. It is used as a moisture and sebum absorber, for skin texture improvement, as a cleaning agent in health and safety pastes, a fragrance carrier in fragrance sachets, a moisture absorber in natural deodorants, an ingredient in natural peeling cosmetics, a foaming and exfoliating agent in shampoos, shower gels, and soaps, and as an addition to anti-cellulite gels and foot scrubs [65].

Perlite is a skincare gem! Its ability to absorb moisture without suffocating the skin is highly valued, especially in facial masks and cosmetic powders for that mattifying effect on oily skin. Moreover, it's fantastic as a mild exfoliant in clay masks, helping to slough off dead skin cells and reveal a smoother complexion. When it comes to toothpaste, perlite works wonders as a polishing agent, ensuring safe cleaning and whitening without damaging enamel. And in body scrubs and soap bars, perlite's exfoliating properties help rid the skin of dry patches, leaving it softer and smoother [97].

Nevertheless, it’s important to consider the particle size and potential abrasiveness of perlite when formulating cosmetic products to ensure that they are suitable and compatible for all skin types [2,5].

Perlite has even more innovative uses beyond its traditional applications! It indeed is a remarkable mineral with infinite applications, **table 5** is a compilation of said uses.

Table 5. Summary of perlite/expanded perlite uses [2,66,98-99].

RAW	EXPANDED	
Sandblasting	***Ambient & Low Temperature Insulation*** (rock decking, concrete floor fill, concrete blocks, bitumized perlite, perlite asphalt, core filler in wallboards, cavity wall insulations, refrigeration plants, portable ice boxes, containers)	***Medium to High Temperature Insulation*** (boiler covering in quite mattresses & in hard-setting compositions, pipe covering in coaxial tubes, compression molded pipe half sections, pour-in-pipe insulation)
Foundry and Steel industries	***High Temperature Insulation*** (foundry cores & molds, ovens, crucible topping)	***Cryogenics*** (super-cooled industrial gases in containers for transport & in stationary plants)
Slag Coagulant	***Oil Well Treatments*** (oil well cementing & low-density mud)	***Abrasive*** (soap, cleaners, polishes, dental compounds, stone wash wheels, discs)
Special Casting Sand	***Flame Resistant*** (fire insulation in safes, rooms, doors, chimney linings)	***Fillers*** (explosives, caulking compositions, paints, plastics, packing for shipping)
Metal Finishing	***Acoustic*** (plasters, mortars, plaster boards, ceiling titles & upper wall insulation, highways sound absorbing walls)	***Adsorption*** (carrier for agrochemicals in pesticides & herbicides, fertilizers bulking, pelletized seeds, catalytic carriers, oil adsorption for pollution control & lean up)
Silica Source	***Horticulture*** (plant rooting, seed starting medium, growing medium, soil conditioner, seed coating, hydroponic, green roots)	***Agriculture Additive/Supplement*** (poultry litter supplement to reduce odor & moisture adsorbent, animal feed anti-caking agent & filler carrier for nutrients/medicines)
///	***Lightweight Aggregate Construction*** (lightweight aggregate concrete, tilt-up panels, bricks & tiles, pottery & refractions, non-load bearing fill, tunnel walls & pipe coating, floors, masonry, roofs, pipe-leveling, insulations)	***Liquid Filtration*** (beer, wine, edible oils, citric acid, sugar, oils, pharmaceuticals, fruit juices, glucose, chemicals, wort, swimming pool water, potable water, storm water, runoff, bio-diesel) ***Air Filtration*** (pre-coat for baghouses)

Special touch on uses of perlite for ceramics and adsorption of heavy metals

Perlite for ceramics

In the art of ceramics, while the artist creates their clay, they use various materials to enhance their creations. These materials can be either organic or inorganic in nature. Perlite, classified as a suitable ceramic flux, helps lower the sintering temperature, providing flexibility, reducing weight, and offering different textures and aesthetic qualities to the clay forms [14,100].

The general composition of ceramic bodies includes various materials like 10-15% potassium and sodium feldspar, 20-35% quartz, 20-40% clay, and 25-23% kaolin. Clays provide plasticity and shaping ease, while kaolin, despite its lower plastic properties, contributes to deformation resistance at high temperatures (due to its high Al_2O_3-aluminium oxide, content), and because it has impurities such as iron (Fe), SO_3 (sulfur trioxide), Ti (titanium), its use for ceramics is not favorable. Feldspathic fluxes play a crucial role in creating the amorphous-liquid phase during firing, essential for sintering and vitrification in ceramics. The alkali content in feldspar significantly impacts its melting properties, affecting the overall ceramic product quality.

Perlite, with its unique mineralogical structure, can serve as a substitute for feldspar in ceramic compositions. Various studies have explored the use of perlite in ceramics, showing promising results. Some of them are recapitulated below:

Mogilski's, L., (1990); research on insulator formulations using perlite led to improved grinding efficiency and enhanced dry and fired strength properties. ***Tarhan, M., and Tarhan, B.,*** (2018); study on ceramic wall tile compositions demonstrated that perlite could be incorporated without compromising technical properties. ***Çakı et al.,'s,*** (2012); investigation into stoneware glaze compositions highlighted perlite's versatility, capable of creating different colors based on iron content and functioning as both a colorant and flux in glazes. ***Tarhan, et al.,'s,*** (2021); findings were regarding the replacement of albite with perlite in varying proportions and compositions at an industrial scale. As perlite content increased, the reduction in total firing shrinkage and achievement of zero water absorption values were significant outcomes, attributed to perlite's enhancement of sintering behavior in ceramic bodies. The study's observations on the impact of perlite on firing shrinkage, high-temperature deformation, strength values, and thermal expansion coefficients provides valuable insights for improving ceramic product quality and service life. The results suggest that incorporating up to 15% perlite in ceramic compositions can lead to less deformation at high temperatures and yield well-formed final products [101-106].

Data from ***Kayacı, et al.,*** (2021); highlighted the positive impact of perlite addition on the sintering behavior of ceramic tile bodies. Perlite's unique shrinkage properties, attributed to its water content and mineralogically amorphous structure, distinguish it from other alkali-containing raw materials during firing. The significant finding of the study regarding the decrease in thermal expansion coefficients due to perlite inclusion underscores the potential for achieving final products with enhanced dimensional stability and favorable deformation properties [107].

The experiments conducted by ***Başar, et al.,*** (2022); were regarding the use of EP in Akçini clay and chamotte clay. The addition of EP at varying rates (0%, 3%, 5%, 7%, respectively) and firing temperatures (950-1200°C (1742-2192°F)) provided valuable insights into the properties of the resulting bodies. It was found that water content tends to increase with the rise in the perlite ratio due to perlite's porous structure. Additionally, the positive effects of perlite additive on color and sintering properties in both clay types, irrespective of firing temperature, highlight the versatility of perlite in ceramic applications. The finding that the recipe with 7% perlite additive leads to deformation in both clays underscores the importance of carefully balancing perlite content for optimal results in ceramic production. The results are illustrated in ***Figure 6*** [100].

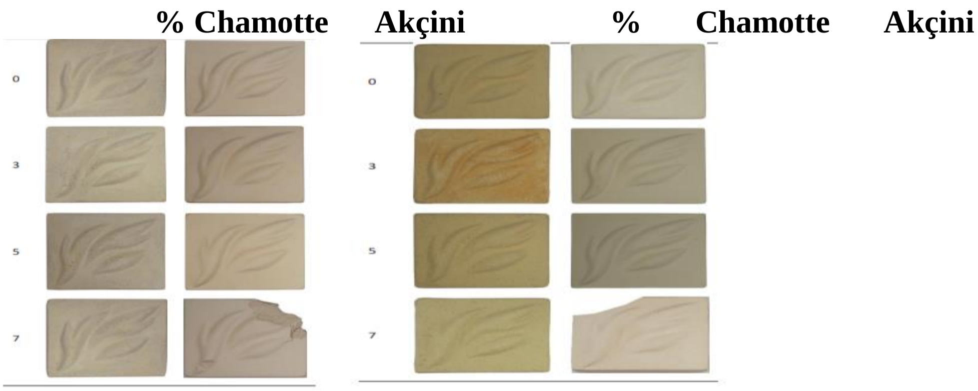
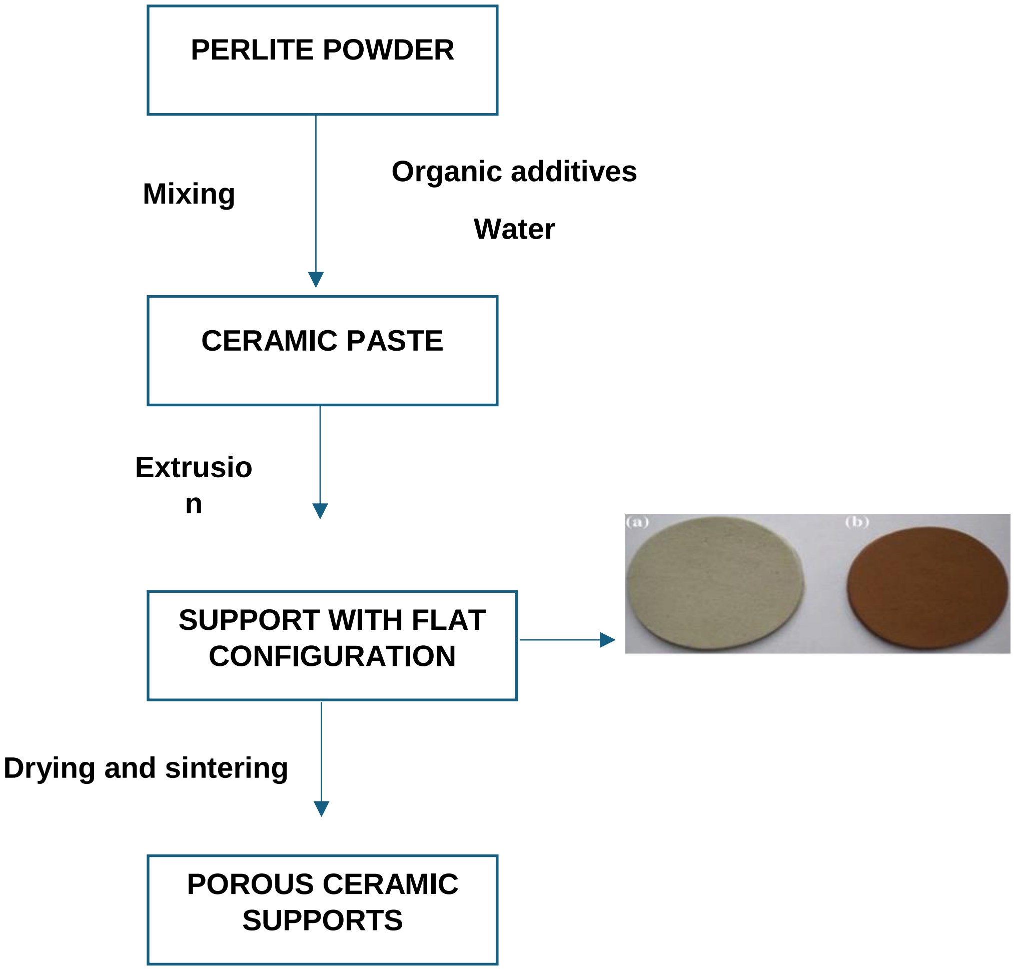


*Figure 6***.** Alterations in colors in the prepared bodies following firing at temperatures of 950°C (1742°F) and 1200°C (2192°F) [100]**.**



Graph 2 and Figure 7. Schematical diagram of producing ceramics from perlite, and **(a)** flat support illustration of Moroccan perlite after drying in 40°C (104°F) and **(b)** after sintering at 1000°C (1832°F), adapted from Majouli, *et al.*, (2011) [101].

Perlite for adsorption of heavy metals

Over the past ten years, there has been a notable rise in the introduction of pollutants originating from human activities, like heavy metals, into the ecosystem. This escalation presents a grave danger to the ecosystem's vitality and balance.

It's crucial to recognize that heavy metals encompass metals and metalloids that are environmentally or biologically significant as toxic substances due to their widespread distribution and abundance. Examples of these metals include lead (Pb), chromium (Cr), copper (Cu), cadmium (Cd), nickel (Ni), and zinc (Zn) [108-109].

Given that perlite is a lightweight, permeable, porous, and inert material with adsorptive properties attributed to Silanol groups (Si-OH) formed on its surface by silicon atoms, it can serve as an effective "agent" for heavy metal adsorption, thereby mitigating the threat the heavy metals pose to the ecosystem. The surface area of perlites varies from 1.22 to 52.9 m^2/g. However, the surface area and pore volume of EP surpass those of unexpanded perlite, with EP exhibiting significantly higher surface area and pore volume (70 times more), making it a promising and cost-effective option for removing heavy metals from wastewater [108,110-112].

Table 6. Adsorption capacities of perlite as an adsorbent for the removal of heavy metals

ADSORBENT	ADSORBATE	ADSORBENT DOSAGE (G/L)	ADSORPTION CAPACITY Q_M (MG/G)	T (°C)	PH	CONTACT TIME (MIN)	% REMOVAL	REF.
P↑/EP	Cu(II)	20	8.62	20	5	90	–	**[110,111]**
P/EP↑	Pb(II)		13.39					
EP	Cr(III)							**[110,113]**
EP	Sr(II)	14	1.14	20	7	90	–	**[32,110]**
-	Ba(II)		2.486					
-	Ag(I)	8	8.46	20	6.5	12	–	**[110-114]**
P/EP↑	Cu(II)	10	1.95			240		
EP	Hg(II)	14	0.35			240		
EP	Pb	10	0.20–2.0	25	7	90	100	**[110-115]**
EP	Cd		0.20–0.95				97.7	
P/EP	Cu(II)	0.2g perlite/100 mL	0.089	32	5	480	99	**[110-116]**
P↓	Ni^{2+}		0.057				99	
P/EP↑	Pb(II)		0.130				78.2	
EP	Cd(II)		0.025				99	
P/EP	Pb	0.2/100mL	8.906	25	6	120	–	**[110-117]**

P/EP-perlite/expanded perlite

6. Conclusions and future prospects

To conclude, perlite is a naturally occurring amorphous glass with a unique composition, rich in silicon oxide, aluminum oxide, and other elements. The formation process gives it remarkable properties that make it a valuable material across various industries. Its lightweight and porous nature, resulting from the rapid cooling of volcanic stone, makes it an exceptional choice for applications such as construction, cryogenic insulation, filtration, and horticulture. In the construction industry, perlite's exceptional thermal characteristics make it an excellent choice for insulation, helping to improve energy efficiency and reduce heat transfer. Its lightweight nature also makes it easier to handle and transport, contributing to overall construction efficiency. Moreover, perlite's porous structure makes it ideal for filtration purposes. Its ability to trap and remove impurities from liquids and gases has made it a popular choice in water treatment systems, air purification, and even in the production of beverages and pharmaceuticals. In horticulture, perlite's porous nature allows for excellent drainage and aeration of soil, promoting healthy root growth and preventing waterlogging. It is commonly used as a soil amendment to improve the structure and nutrient retention of growing media.

Looking ahead, the future prospects for perlite are promising. Ongoing research and development may lead to further advancements in its applications. For instance, in the field of drug delivery systems, perlite's inert and porous nature could potentially be utilized as a carrier for controlled release of medications. Additionally, perlite's use in ceramics has shown promise in reducing shrinkage during firing, leading to improved quality and durability of ceramic products. This opens up possibilities for its increased utilization in the ceramics industry. Furthermore, perlite's ability to adsorb heavy metals makes it a potential candidate for environmental remediation, helping to purify solutions and remove pollutants.

To summarize, perlite's versatility and unique properties make it a valuable material with exciting future prospects. As research and exploration continue, we can expect to see further innovations and applications in various industries. It's truly an intriguing mineral with endless possibilities!

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