UPGRADING OF RAW PERLITE BY A DRY MAGNETIC TECHNIQUE

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Abstract
Perlite of composition SiO$_2$ 73.6%, Al$_2$O$_3$ 12.4%, Fe$_2$O$_3$ 1.25%, MgO 0.15%, Na$_2$O 2.99%, K$_2$O 4.18%, H$_2$O$^+$ 3.17%, H$_2$O$^-$ 0.2%, and found to contain 89.4% of amorphous phase and 10.6% of crystalline phase, the latter consisting of feldspars, biotite, quartz, magnetite and chlorite, was studied. Due to its largely amorphous nature, chemical composition and melting behaviour, perlite can be used in the manufacture of ceramics. For the glass industry, on the other hand, an impediment, albeit the only one, is the iron content, so that the iron-bearing minerals must be removed, which can be accomplished by dry magnetic separation. Laboratory and pilot-plant separation experiments carried out with these minerals showed that the Fe$_2$O$_3$ content cannot be reduced to below 0.65% owing to small inclusions of iron-bearing minerals that remain in the other minerals, or in the amorphous particles. Perlite with an Fe$_2$O$_3$ content below 0.7% and grain size of less than 1 mm can, however, be used in the production of coloured glass containers.

INTRODUCTION

Perlite is a hydrated volcanic glass of rhyolitic composition containing 1 to 5 % of combined water. It belongs to the same family of volcanic glasses as obsidian, pitchstone, pumice and scoria. Its most important property is its ability to expand to about 20 times its original volume when heated to a temperature within its softening range. The result is "expanded perlite", a product of low density, low thermal conductivity and high sound absorption.
Thanks to its characteristics expanded perlite is used in a variety of industrial and construction applications, as well as in agriculture. Concomitant with the growing interest in the expanded material, the possibility of using crude perlite as a raw material in some applications is also beginning to draw attention of researchers.

Raw perlite, of different fractional grain sizes and bulk densities, has already been successfully tested in the ceramics industry as a component of ceramic bodies for floor and wall tiles [1], as an inorganic additive to serve as a drying agent, or as a sintering auxiliary in a ceramic body [2], as a mineral additive in the technology of self–glazing and pigmentation of ceramic tiles [3].

A very important application of raw perlite is its use as a raw material in the synthesis of zeolites [4]. Due to its physical characteristics — uniformity coefficient, hydraulic size, density and porosity, perlite constitutes a good filter material [5]. Due to SiO₂/Al₂O₃ ratio, alkaline content, homogeneity and amorphous structure of perlite, two very new applications are as a mineral additive instead of clay in wet phosphoric acid process [6] and as an additive in the production of ceramic glass [7].

**PROPERTIES OF PERLITE**

The most important physical properties are listed in Table 1. The perlite studied originated in the island of Milos and was supplied by Habonim Industries, Moshav Habonim. It has a light gray colour and a vitreous luster. The presence of vesticules is the most obvious feature. Phenocrysts of quartz and feldspar measuring 1 to 2.5 mm are imbedded in the glass matrix. Biotite flakes can also be observed with the naked eye. The perlitic glass exhibits a perfect and encircling fluidal phenomena (Fig. 1).

The granulometric distribution of the crushed perlite is illustrated in Fig. 2. Most of the particles are contained in the 20 to 70 mesh size range. A microscopic analysis of various sieved fractions indicated that the feldspars and quartz are present in all granulometric fractions. The chlorite is mainly contained in the large
Table 1 Physical properties of raw perlite

| Property            | Description                                      |
|---------------------|--------------------------------------------------|
| Colour              | Grey, brown, black, green                        |
| Luster              | Pearly, vitreous, resinous, pitchy               |
| Density             | 2.3 to 2.8 g/cm³                                 |
| Bulk density        | 1.2 to 2.35 g/cm³                               |
| Hardness            | 5.5 to 7 (Mohs' scale)                          |
| Melting point       | 760 to 1320º C                                  |
| Expansion temperature| 600 to 1100º C                                  |
| Expansion ratio     | 10 to 20 (volume)                               |
| Structure           | Amorphous                                        |

Fig. 1 Thin–section microphotograph (x30) of perlite showing fluidal phenomena (see colour plate I at back of issue).
size fractions (+ 35 mesh), while biotite and magnetite are concentrated in the smaller fractions (−70 mesh). They appear as individual crystals or as inclusions in the other minerals and in the glass grains. Biotite is also abundant in the −50 + 70 mesh fraction.

Chemically, crude perlite is a hydrated aluminium silicate. A series of chemical analyses of perlite ores of different origins is given in Table 2. It will be seen that perlite is characterised by a high silica (≥65%) and alumina (11 to 17%) content. Noteworthy is also the alkaline content (7 to 8.5%).
Table 2  Chemical analyses (mass %) of raw perlite of various origins

| Oxide   | 1    | 2    | 3    | 4    | 5    | 6    | 7    |
|---------|------|------|------|------|------|------|------|
| SiO₂    | 65.21| 68.95| 69.01| 70.9 | 71.73| 73.8 | 74.1 |
| Al₂O₃   | 11.6 | 16.08| 14.21 | 13.7 | 13.64| 12.4 | 13.3*|
| TiO₂    | n.d. | n.d. | 0.22 | n.d. | n.d. | 0.16 | 0.05 |
| Fe₂O₃   | 1.01 | 1.65 | 1.45 | 1.9  | 1.71 | 1.25 | 0.5  |
| MgO     | n.d. | 2.12 | 0.39 | 0.05 | 0.56 | 0.21 | 0.1  |
| CaO     | n.d. | 0.86 | 1.57 | 1.9  | n.d. | 1.7  | 0.6  |
| Na₂O    | 3.85 | 3.08 | 3.2  | 3.6  | 3.55 | 2.99 | 3.5  |
| K₂O     | 3.44 | 5.34 | 3.94 | 3.4  | 4.15 | 4.18 | 4.6  |
| H₂O⁺    | n.d. | n.d. | 5.77 | 3-4  | 3.47 | 3.17 | 3.5  |
| H₂O⁻    | n.d. | n.d. | 0.24 | n.d. | n.d. | 0.2  | 0.1  |

H₂O⁺  Loss on ignition at 800°C
H₂O⁻  Loss at 105°C
n.d.  not determined
*     includes P₂O₅ and MnO

1  Siberia [8]  2  Sardinia [8]
3  Korea [9]  4  El Rosario (El Salvador) [10]
5  Yugoslavia [3]  6  Milos (Greece), the analysed perlite
7  Sorroco (New Mexico) [11]

Mineralogically, perlite consists of a hydrated natural volcanic glass in which are embedded small amounts (up to 20%) of crystalline inclusions. Table 3 shows the mineral phases detected in perlites from various places all over the world. In particular, perlite studied in this work contains 89.4% by volume of the amorphous phase and 10.6% by volume of the crystalline phase consisting of plagioclase (5.5%), alkali feldspar (0.9%), biotite (3.0%), quartz (0.8%), magnetite (0.3%) and traces of chlorite. The physical characteristics of the mineral impurities are shown in Table 4.

The commercial value of perlite is determined, among other things, by the percentage of crystallinity. The most common contaminant in perlite is crystalline silica which may occur in a number of polymorphic forms, the most of which are quartz, cristobalite and tridymite. Experience has shown that cristobalite and
Table 3  Mineral phases detected in perlite throughout the world

| Place            | Mineral phases                                      |
|------------------|-----------------------------------------------------|
| New Mexico [11]  | quartz, feldspar, biotite                           |
| El Salvador [10] | plagioclase, amphibole, hyperstene, ore             |
| Korea [9]        | plagioclase, biotite, opaque minerals, traces of hornblende, apatite, zircon and sanidine |
| Sardinia [8]     | quartz, mica, feldspars                             |

Table 4  Physical characteristics of minerals

| Mineral   | Formula                               | Colour          | Luster          | Hardness | Density     | Magnetic properties |
|-----------|---------------------------------------|-----------------|-----------------|----------|-------------|--------------------|
| Plagioclase feldspar | (NaSi,CaAl)AlSi$_2$O$_8$ | White to grey | Vitreous, pearly | 6.0-6.5  | 2.63-2.76   | very weakly paramagnetic or diamagnetic |
| Orthoclase | KAlSi$_3$O$_8$                        | Red, grey, white | Vitreous        | 6.0-6.5  | 2.5-2.6     | Diamagnetic         |
| Quartz    | SiO$_2$                               | Colourless, all colours | Vitreous  | 7        | 2.65-2.66   | Diamagnetic         |
| Biotite   | K$_2$(Mg,Fe)$_3$(OH,F)$_2$.AlSi$_3$O$_10$ | Black, brown | Pearly          | 2.0-3.0  | 2.7-3.1     | Paramagnetic        |
| Chlorite  | (Mg,Fe)$_3$Al$_2$Si$_3$O$_10$. (OH)$_8$ | Green, brown   | Pearly          | 2.0-2.5  | 2.7         | Weakly paramagnetic |
| Magnetite | FeO.Fe$_5$O$_3$                       | Iron black      | Metallic        | 5.5-6.5  | 4.9-5.3     | Ferromagnetic       |

Tridymite are very rare in perlite. Because perlite is very high in total silica, any determination must be based on a technique sensitive only to the crystalline portion since the results cannot be checked by an analysis for total silica. Techniques which can discriminate between crystalline and amorphous silica include infrared spectroscopy, XRD, polarised light microscopy, differential solubility and heavy mineral separation.
EXPERIMENTAL

Magnetic separation experiments were performed in two stages, viz. laboratory and pilot, with the aim of removing the iron-bearing minerals. The laboratory tests were carried out with the Frantz isodynamic separator on various granulometric fractions. The longitudinal slope of the cutie was set to 16° and the cross slope 19°. Table 5 shows the magnetic induction of the Frantz separator as a function of the electric current while the separation results are summarised in Table 6.

Table 5 Frantz isodynamic separator: data

| Current I (Amperes) | 0.41 | 0.81 | 1.2  | 1.4  | 1.5  |
|---------------------|------|------|------|------|------|
| Magnetic induction B (Gauss) | 4000 | 8000 | 12000| 14000| 15000|

Table 6 Magnetic separation in Frantz isodynamic separator

| Particle size (ASTM mesh) | 0.25 | 0.50 | 1.00 | 1.25 | 1.50 | Total |
|---------------------------|------|------|------|------|------|-------|
| M | NM | M | NM | M | NM | M | NM | M | NM | M | NM |
| -20+35 | 0.6 | 99.4 | 0.6 | 99.4 | 1.3 | 98.7 | 0.9 | 99.1 | 0.8 | 99.2 | 5.7 | 94.3 |
| -35+50 | 0.6 | 99.4 | 0.6 | 99.4 | 1.5 | 98.5 | 1.5 | 98.5 | 0.6 | 99.4 | 5.8 | 94.2 |
| -50+70 | 0.9 | 99.1 | 0.7 | 99.3 | 1.5 | 98.5 | 1.2 | 98.8 | 0.7 | 99.3 | 6.3 | 93.7 |
| -70+100 | 2.5 | 97.5 | 0.9 | 99.1 | 1.6 | 98.4 | 0.9 | 99.1 | 0.6 | 99.4 | 8.1 | 91.9 |

M magnetic fraction (wt. %)
NM nonmagnetic fraction (wt. %)

All the magnetic fractions removed in different passes and the non-magnetic fraction were examined under a polarising microscope. Distributions of minerals during the separation experiments for -35+50 mesh and -70+100 mesh classes are presented in Tables 7 and 8.
Table 7  Mineral distribution of various fractions in Frantz separator for -35+50 mesh

| Magnetic pass (A) | Mineral phases (%) |   |   |   |   |   |
|------------------|--------------------|---|---|---|---|
|                  | Amorphous material | Feldspar | Biotite | Quartz | Magnetite | Chlorite |
| 0.25             | 30.3               | 9.6     | 6.8    | 0.9    | 52.4      | -        |
| 0.50             | 6.6                | 1.6     | 90.7   | 0.3    | 0.8       | -        |
| 0.75             | 11.3               | 0.9     | 86.8   | -      | 0.9       | -        |
| 1.00             | 15.2               | 0.6     | 19.5   | -      | 0.3       | 64.4     |
| 1.25             | 77.5               | 7.1     | 6.7    | 1.2    | 0.3       | 7.2      |
| 1.50             | 95.5               | 1.9     | 1.7    | 0.3    | 0.2       | -        |
| 1.75             | 95.5               | 3.0     | 0.5    | -      | -         | -        |
| nonmagnetic      | 95.6               | 2.1     | 0.5    | 1.8    | -         | -        |

calculated from a total of 600 counted particles

Table 8  Mineral distribution of various fractions in Frantz separator for -70+100 mesh

| Magnetic pass (A) | Mineral phases (%) |   |   |   |   |   |
|------------------|--------------------|---|---|---|---|
|                  | Amorphous material | Feldspar | Biotite | Quartz | Magnetite | Chlorite |
| 0.25             | 60.2               | -       | -      | -      | 30.8      | -        |
| 0.50             | 58.6               | 12.5    | 28.3   | -      | 1.6       | -        |
| 0.75             | 9.8                | 3.6     | 30.0   | -      | 0.2       | 56.4     |
| 1.00             | 56.4               | -       | 12.5   | -      | 0.7       | 30.4     |
| 1.25             | 90.3               | 5.9     | 2.7    | 0.6    | 0.5       | -        |
| 1.50             | 92.4               | 7.6     | -      | -      | -         | -        |
| 1.75             | 96.8               | 3.5     | -      | 0.3    | -         | -        |
| nonmagnetic      | 94.4               | 4.8     | -      | 0.8    | -         | -        |

calculated from a total of 530 counted particles

The pilot stage was conducted by Inprosys, Inc. (High-force magnetic separators) and Osna Equipment, Inc. (Permroll). Table 4 shows that the iron-bearing minerals are distinguished chiefly by their magnetic properties. Thus, their magnetic separation requires a multistage operation: first to remove ferromagnetic minerals and then to inter—separate the paramagnetic ones. Results of the pilot—plant stage are presented in Table 9 and 10, together with the test parameters.
Table 9  Magnetic separation tests by *Inprosys, Inc.*

| Test no./Product | Roll speed [rpm] | Feed rate [t/h/m] | % weight | % Fe$_2$O$_3$ |
|------------------|------------------|-------------------|----------|--------------|
| 1 Feed           |                  |                   |          |              |
| Magnetic 1       | 150              | 3                 | 100      | 1.25         |
| Non-magnetic 1   | 130              |                   | 2.98     | 1.10         |
| Magnetic 2       |                  |                   | 89.86    | 0.69         |
| Non-magnetic 2   |                  |                   |          |              |
| 2 Feed           | 160              | 5.8               | 100      | 1.25         |
| Magnetic 1       |                  |                   | 6.20     | 8.90         |
| Non-magnetic 1   | 130              |                   | 3.58     | 1.20         |
| Magnetic 2       |                  |                   | 90.22    | 0.73         |
| Non-magnetic 2   |                  |                   |          |              |
| 3 Feed           | 150              | 4.6               | 100      | 1.25         |
| Magnetic 1       |                  |                   | 6.85     | 7.30         |
| Non-magnetic 1   | 125              |                   | 3.21     | 1.20         |
| Magnetic 2       |                  |                   | 89.94    | 0.71         |

Table 10  Magnetic separation by *Osna, Inc.*

| Test no./Product | Roll speed [rpm] | Weight [%] | Feed rate [t/h/m] | Fe$_2$O$_3$ [%] |
|------------------|------------------|------------|-------------------|----------------|
| 1 Feed           |                  |            |                   |                |
| Magnetic 1       | 250              | 100        | 2.36              | 1.25           |
| Magnetic 2       | 175              | 15.99      |                   | 2.39*          |
| Magnetic 3       | 125              | 9.01       |                   | 0.68           |
| Non-magnetic 3   |                  | 65.16      |                   |                |
| 2 Feed           | 200              | 100        | 2.25              | 1.25           |
| Magnetic 1       |                  | 7.78       |                   | 2.81*          |
| Magnetic 2       | 175              | 18.02      |                   | 0.71           |
| Non-magnetic 2   |                  | 74.02      |                   |                |
| 3 Feed           | 200              | 100        | 4.29              | 1.25           |
| Magnetic 1       |                  | 10.11      |                   | 3.56*          |
| Magnetic 2       | 175              | 9.22       |                   | 0.70           |
| Non-magnetic     |                  | 80.2       |                   |                |
| 4 Feed           | 225              | 100        | 5.84              | 1.25           |
| Magnetic 1       |                  | 10.83      |                   | 2.17*          |
| Magnetic 2       | 200              | 6.68       |                   | 0.70           |
| Magnetic 3       | 150              | 22.15      |                   |                |
| Non-magnetic 3   |                  | 59.83      |                   | 0.65           |

(*) calculated
DISCUSSION

The purpose of the present paper is to present a new process of upgrading which enables the use of crude perlite as a raw material in the manufacture of coloured glass containers. A typical batch for such a production is composed of sand, limestone, soda ash and alumina as main ingredients, and several other materials such as feldspars, sodium nitrate, barytes, cullet etc. Low-iron perlite constitutes a source of silica and also adds alumina and alkalis. Moreover, due to its amorphous nature, perlite has a more reactive melting behaviour than other materials used for this purpose.

The main problem is the iron content which is usually greater than 1.0% (see Table 2). In particular, the analysed perlite contains 1.25% Fe$_2$O$_3$. Thus diminution of the iron content became the first task. The simplest and the cheapest engineering method for solving the problem is dry magnetic separation. Two reasons render this possible:

1. Fe$_2$O$_3$ is contained in magnetite (ferromagnetic), and in biotite and chlorite (both paramagnetic, as stated in Table 4), and can be magnetically separated.

2. Microscopic studies showed that if the material is crushed, liberation of minerals can be achieved to some extent.

Dealing with perlite as a raw material for glass production, one has to take into account two other factors besides the iron content:

a. Particle size distribution which influences both the melting process and the glass quality

b. The water content. A customer must know that, out of one tonne of perlite he buys, 10 to 50 kg represent water content which will be lost upon melting the material. Besides, the water will cause expansion of perlite and attention has to be paid to the amount of material that must be introduced into a container in which the melting takes place.
In order to study the behaviour of minerals in a magnetic field of different strength, tests were made with a laboratory Frantz separator. Table 6 shows that better separation is achieved with smaller particles but the differences are of little practical significance. However, with the -70+100 mesh fraction, a better liberation of particles was achieved, improving the results.

Tables 7 and 8 show the mineral distribution of magnetic fractions (impurities) from two granulometric classes following separation at different values of the magnetic field strength. It was expected that in a weak magnetic field the ferromagnetic minerals would be removed and that when the magnetic field strength is increased, paramagnetic particles would be removed. Microscopic analysis showed, however, that magnetite had not been entirely liberated and still appeared as small inclusions in other minerals. This is why diamagnetic particles of the amorphous phase, feldspar and quartz (which contain inclusions of magnetite) had been removed with the magnetic fraction even at weak magnetic field intensities.

With respect to biotite, most of it is removed at between 0.5 and 1.0 A, thus behaving like a paramagnetic mineral. It seems that a part of biotite has a high content of iron and can be separated at 0.5 A (see Table 7). This iron-rich biotite is found in +50 mesh granulometric fractions. However, even biotite was not entirely removed, remaining as inclusions in glassy grains.

Another iron-bearing mineral in perlite is chlorite which is completely separated at field strengths lower than 1.75 A. Feldspars and quartz are removed in different magnetic passes due to the inclusions of magnetite or biotite which they contain. This is also valid for particles of glassy material. What determines the limit beyond which these particles cannot be separated is the size and the number of inclusions. It will be seen that by increasing the magnetic field strength above 0.75 A the quantity of the removed amorphous glassy material also increases. At 0.25 A and 0.5 A the main phases separated are magnetite and biotite, respectively. This is not valid for large-sized particles (+35 mesh) where good liberation was not achieved.

Figures 3 to 7 show a succession of magnetic fractions removed on Frantz separator, and the final non—magnetic fraction of the -100+70 mesh fraction.
Fig. 3  A photomicrograph (x80) showing −70+100 mesh magnetic fraction removed with Frantz separator at 0.25 A. M=magnetite, A=amorphous perlite (see colour plate II at back of issue).

Fig. 4  A photomicrograph (x110) of −70+100 mesh magnetic fraction separated with Frantz separator at 0.5 A. showing biotite flakes (see colour plate III at back of issue).
Fig. 5  A photomicrograph (x110) of -70+100 mesh magnetic fraction separated with Frantz separator at 1 A. A major part of this fraction is composed of chlorite (C) and biotite (B) flakes (see colour plate IV at back of issue).

Fig. 6  A photomicrograph (x110) of -70+100 mesh magnetic fraction obtained with Frantz separator at 1.25 A showing particles of amorphous phase with inclusions (see colour plate V at back of issue).
Magnetic fraction separated at 0.25 A shown in Fig. 3 is made up almost entirely of grains of amorphous perlite with inclusions of magnetite and very rare inclusions of biotite and grains of free magnetite. The magnetics removed at 0.5 A shown in Fig. 4 consist almost entirely of biotite. Figure 5 shows the magnetic fraction at 1.0 A, the major phase being represented by chlorite.

Beginning with 1.25 A, the main magnetic phase is made up of amorphous material, with inclusions of magnetite and/or biotite. Figure 6 depicts such grains that were separated at 1.25 A. The non–magnetic fraction contains almost exclusively particles of amorphous material, frequently with inclusions of biotite or very small magnetite (Fig. 7) and grains of feldspars and quartz (both diamagnetic).
It can be concluded that the size of particles affects the results not so much through achieving better liberation of minerals due to more finely crushed particles, as was thought at the beginning, but rather through proportion between the particle size and the inclusion content.

During the pilot experiments the best separation of iron-bearing minerals was achieved by using the Permroll separator in a three-stage magnetic separation, at the feed rate of 5.84 tonnes per hour per meter width of the roll. The Fe$_2$O$_3$ grade of the non-magnetic fraction obtained with this device was 0.65%, at the material recovery of 59.83%. It will also be seen from Tables 9 and 10 that a better recovery (more than 80%) can be reached if the Fe$_2$O$_3$ content is reduced to as low as 0.69 – 0.70%. It will be shown later that this content is low enough to permit the use of raw perlite in the production of coloured glass containers. Besides, the laboratory experiments proved that the particle size has no considerable influence on the material recovery so that additional crushing will not improve substantially the results.

The upgraded perlite obtained with Permroll was divided into three granulometric classes, in order to see if the size of particles has any influence on the mineralogical content. The results of the microscopic analyses are shown in Table 11. It can be seen that the more finely ground the product is, the more the impurity concentration decreases. Feldspar is abundant in larger sized classes while quartz is concentrated in smaller fractions. Biotite is found as inclusions in amorphous glass particles. It seems that the presence of these inclusions is responsible for relatively high Fe$_2$O$_3$ content in the non-magnetic product.

| Particle size (mesh) | Mineral content | (vol.%)
|----------------------|-----------------|---------|
|                      | Amorphous phase | Feldspar | Quartz | Biotite |
| -18+35               | 91.8            | 6.8      | 0.5    | 0.9     |
| -35+50               | 92.2            | 5.9      | 1.2    | 0.7     |
| -50                  | 92.5            | 4.7      | 2.4    | 0.4     |
The upgraded perlite was successfully tested at the Phoenicia plant, Yerucham, as a mineral additive for the production of coloured glass containers. Four specifications were established for perlite so that it can be used as a raw material in this industry:

1. Chemical: Fe$_2$O$_3$ concentration less than 0.7%; SiO$_2$/Al$_2$O$_3$ ratio and the alkaline content of about 8%

2. Physical: grain size of less than 18 mesh (1 mm)

3. Amorphisation: reactivity of perlite

4. Homogeneity and uniformity of the material.

CONCLUSIONS

1. Its amorphous nature and chemical composition, together with its melting point make crude perlite a very suitable raw material for coloured glass industry. Its potential depends mainly on the iron content.

2. Fe$_2$O$_3$ is found in magnetite, biotite and chlorite. Therefore, the simplest engineering solution for upgrading is the dry magnetic separation of these iron–bearing minerals. The basic unit operation has to be executed in several stages; first to scalp the ferromagnetics and then to remove the paramagnetic minerals.

3. The magnetic separation experiments did not succeed in reducing the Fe$_2$O$_3$ content below 0.65%. The reason for this is the smallness of the inclusions of biotite and/or magnetite in the non–magnetic fraction.

4. Perlite with iron content below 0.7% and maximum grain size of 18 mesh (1 mm) can be used in the manufacture of coloured glass containers.
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