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Industrial minerals: Significance and important characteristics

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1 Introduction and definitions

Industrial minerals have been exploited by man for many thousands of years and have contributed to some of the most important cultural developments. In earlier periods of history people used mineral pigments and hard stones for grinding and cutting. Since then technology has advanced in major ways; nevertheless similar materials are still used today for similar applications. Nowadays, industrial minerals and rocks are the most important raw materials for most industrialized countries.

Establishing an adequate definition for industrial minerals and rocks is difficult and several have been proposed. For example Bates (1994) defines them as follows: *"an industrial mineral is any rock, mineral, or any other naturally occurring substance of economic value, exclusive of metallic ores, mineral fuels and gemstones; one of the nonmetallics"*. In fact industrial minerals have been used in the past as a synonym to nonmetallic materials (Harben & Bates, 1990). There are two shortcomings in this definition, firstly that several metallic ores such as bauxite, ilmenite, chromite, pyrite and Fe-oxides are also industrial minerals and secondly the term industrial minerals can be used also for manufactured materials such as cement, refractories or abrasives . A more complete and general definition is given by Scott (2009) whereby *"industrial minerals are a loose grouping of products made from Earth materials that are not a source of a metal or energy"*.

The most important characteristic of industrial minerals is that they have one or more important physical or chemical properties or both. Therefore an alternative definition is proposed, which takes into account this important characteristic: *"industrial minerals and rocks are Earth materials utilized because of their characteristic physical and/or chemical properties and not because of their metal content and which are not energy sources"*. This definition includes five major groups of raw materials:

a) Raw materials which are utilized by the industry as minerals (e.g. talc, asbestos, micas, feldspars) or bulk rocks (e.g. bentonite, perlite, limestone) because of their special physical and/or chemical properties, such as mechanical strength, colour, viscosity, inertness, high melting point, cation exchange capacity etc.
b) Raw materials which are source of non-metals such pyrite for sulphur, apatite for phosphorus, borates for boron and fluorite for fluorine.
c) Raw materials which may be source for metals such as bauxite for Al, chromite for Cr or ilmenite for Ti, but which may also be used in certain industrial applications because of their characteristic physical and chemical properties. Hence, bauxite and chromite can be used as refractory materials and ilmenite is used as a source of TiO_2 pigment. Magnesite (source of Mg), beryllium minerals (sources of Be) and sylvite (source of K) are included in this group as well. In contrast Ni-laterites, are not included,

although nickel is present in non-metallic phyllosilicate minerals (serpentine, smectite, chlorite, talc). Note that these phyllosilicates may form important industrial mineral deposits in other geological environments.

d) Natural construction materials including building and ornamental stones and aggregates (granite, marble, limestone sand and gravel etc).
e) Synthetic materials which may be monomineralic or may consist of several phases, such as zeolites, industrial diamonds, lime, dead burnt or caustic magnesite, smectite etc. They are synthesized from i) amorphous gels, ii) from other precursor minerals or from volcanic glass and iii) from industrial waste from the mining industry. Other materials, such as glass or cement are made of industrial minerals but must be considered as manufactured industrial products, not real industrial minerals. *Geopolymers* is a new type of materials which can be included in this group (Xu & van Deventer 2002; Komnitsas & Zaharaki, 2007).

Hence the term industrial rocks and minerals includes a large number of raw materials and synthetic products, the most important of which are given in Table 1 of Scott (2009).

There are a series of terms used to describe deposits of industrial minerals and rocks. In economic geology the term *ore* refers to an assemblage of minerals, which can be mined, processed and sold for profit. Also the term *gangue* refers to a material without economic significance, which is associated with the ore. It follows that the term ore cannot be used for raw materials, which are utilized in bulk form without separation of the gangue through processing. This is usually the case for industrial rocks such as limestone, perlite and bentonite. In contrast other industrial rocks, such as kaolin may undergo significant processing to increase the concentration of kaolin minerals and can thus be considered as ores. For instance the processing of Georgia kaolins includes delamination, magnetic separation, froth flotation and bleaching. However this is not the case for other kaolins (e.g. the Cornish kaolins, although some grades are processed by delamination, magnetic separation and bleaching). Several industrial minerals such as magnesite and feldspar undergo beneficiation using various processing methods and hence they can be considered as ores.

The term *prospecting* describes the process of locating industrial mineral and rock resources. Usually it is used as a synonym for *exploration*. Nevertheless the term exploration may be used in a different sense as well. It may refer to the investigation of a deposit after its discovery, in order to determine its size, shape and reserves, although the latter are included to the terms assessment or evaluation (see below). Also the term *development* refers to all these preparation actions necessary for exploitation of an industrial rock or mineral deposit, mainly the excavation of the quarry and the construction of the processing plant. Often the term development includes also exploitation of the deposit.

Two additional terms, which differentiate industrial mineral and rock deposits from ore deposits are *evaluation* and *assessment*. Although the two terms are often used as synonyms, the term evaluation includes economic parameters as well. Assessment is the examination of those physical and/or chemical properties that are important for the industrial applications of the raw material. The properties examined have to fulfill certain specifications. Assessment includes also geological, mineralogical and petrographic study of the deposit. On the other hand evaluation except for assessment includes also examination of factors that are likely to affect mining, processing, maintenance and transportation costs (such as location, topography, position of water table) and markets (Scott, 1987). Evaluation may also include estimation of reserves, examination of suitable mining and processing methods (i.e. it may comprise also exploration of the deposit) as well as a reappraisal of markets.

2 Special features of the industrial rocks and minerals

2.1 Place and unit value

Place value is a term used widely for industrial minerals and rocks. It expresses the influence of the geographic area in which an industrial rock or mineral is mined or quarried on its market value and reflects the importance of the value of the product in relation to its market (Scott, 1987). The *unit value* is the real market value of the product and depends on the development of a market for this mineral and the ability of the mining companies to *add value* on their end product. Added value is produced from processing which yields materials with better properties. For instance some kaolin grades for paper coating are produced by delamination, magnetic separation, flotation or leaching (Murray, 2007). Processing may sometimes yield high added value products for highly specialized markets. Typical examples are the acid activated bentonites which find application as bleaching earths for decolourising edible oils (Christidis *et al.*, 1997), or the organophilic bentonites, which are utilized in the formulation of nanocomposites (de Paiva *et al.*, 2008). The production of added value industrial mineral products is feasible only when there is market available to consume these end products.

Usually industrial mineral and rock products with high place value have low unit values. For example sand and gravel or crushed aggregates are valuable only when they are consumed close to the area from which they are mined. Their value as a resource diminishes even further when they are transported away from that area, because their unit value is low and transport costs increase significantly the market value. In fact transport costs are a dominant component of the value paid by the customer (Manning, 1995). Hence aggregates in general have high place value. Nevertheless there are exceptions in this rule. The development of superquarries operating in remote areas such as those in NW Scotland, which extract hard rock aggregates, and which then are loaded to large vessels, has allowed transportation of aggregates to the Gulf coast states of the USA, the south east England and countries of north Europe (Manning, 1995). In this case the increasing demand for aggregates coupled with the lack of suitable raw materials in the consuming countries and the relatively low freight costs has allowed transportation of industrial rocks with high place value over long distances. Industrial rocks which are sold in expanded form (perlite, vermiculite) have also high place value; with a few exceptions, perlite is not transported as expanded material, but it is carried in unprocessed bulk form and undergoes expansion after transportation.

On the other hand there are many industrial rocks and minerals which have a unique physical property or combination of properties and therefore are valued by the industry. These properties impart a high unit value to the industrial minerals, which can be transported worldwide. These products are traded internationally and thus have taken a place in the international commerce. Typical examples are the kaolin deposits of Cornwall, UK (although currently there are cheaper supplies from Brazil and China), or the bentonite deposits of Milos, Greece. Transport may be facilitated by access to sea routes. For example although there are important perlite reserves in New Mexico (Barker *et al.*, 2002), perlite from Greece and China is imported to the eastern and western US respectively, because sea transport is less expensive than land transport. A high unit value may be imparted also by the rarity of an industrial mineral, which is consumed by the industry. For example currently deposits of borate minerals, vermiculite, lithium minerals and rare earth element minerals are exploited only in a few countries in the world.

2.2 Significance of physical properties

By definition industrial minerals and rocks are utilized because of their important physical and chemical properties either as raw materials or after processing. These properties remain essentially unchanged in the end use after processing (Bates, 1969). Moreover the mode of occurrence of rocks and minerals in the field is closely related to the way in which they will be used by the industry. In some cases, the raw material cannot be utilized without processing; the latter yields new phases which are utilized because of some important physical properties. A typical example is refractories, in which the raw materials are usually fired at high temperatures to form oxides or silicates. Magnesite and dolomite are calcined at temperatures in excess of 1500°C to produce dead burnt magnesite and dolomite respectively. Similarly bauxite is fired at high temperatures to form Al_2O_3 and minerals of the kyanite group (kyanite, sillimanite, andalusite) are fired to form mullite before their use as refractories. Both dead burnt magnesite (i.e. periclase) and mullite are in the form of minerals and have high melting points.

In some industrial minerals and rocks special treatments may impart new physical properties to the raw material. For example the treatment of bentonite with inorganic acids, known as acid activation (Christidis, 2009, this volume), yields materials with large number of acid centers and high sorption capacity, which can adsorb colouring compounds and decolourize and stabilize crude edible oils. This sorption capacity is not present in the raw materials. Similarly expansion of perlite or exfoliation of vermiculite yields lightweight aggregates with significant insulation properties, which are not observed in the untreated raw materials.

2.3 Competition, substitution and synthesis

Different industrial minerals and rocks may have similar physical and chemical properties. Since they are used by the industry for these properties it follows that there is competition for end uses and that one commodity may substitute for another in a certain industrial application. Typical examples are the substitution of kaolin by calcite or talc in paper plastic or paint fillers, the substitution of feldspar by nepheline syenite in ceramics the substitution of bentonite by palygorskite in the drilling industry etc. Substitution is affected by the intrinsic properties of the raw material, the local availability of the resource, the price and technical requirement (Clarke, 1987). An example of the significance of intrinsic properties is the palygorskite drilling muds, which do not flocculate in the presence of electrolytes. Therefore, they have superior rheological properties and successfully replace bentonites in drilling using sea water. Local availability is an important factor affecting substitution of industrial minerals, because by tradition local industry is based on indigenous sources in order to suppress production costs. For example the local availability of kaolin, calcite or talc partly determines which type of filler will be used in the paper industry. The technical superiority of an imported material against local resources may encourage the development of appropriate technology to use local resources more effectively. Hence successful processing may improve the properties of local resources and increase their added value against imported raw materials.

The tendency for substitution of industrial raw materials and technological change varies with the type of industry and depends on the general economic climate, management and operational flexibility (Clarke, 1987). In periods of economic recession substitution of raw materials is less likely to occur, because the industry usually undertakes minimum risks. Also substitution may be imposed by environmental reasons. In this respect zeolites have replaced phosphates in powder detergents. They are considered environmentally friendly because they act as deflocculants and water softeners and they do not contribute to eutrophication of natural waters, and thus reduce the environmental impact.

Synthetic industrial minerals often are competitors of their natural counterparts or of other raw materials. Although they have a higher production cost which increases their unit value they are preferred in certain applications in which product quality is of top priority for two reasons: a) their composition and hence properties does not vary b) their physical properties may be tailored according to the specifications of the particular industry c) often new species with superior properties can be synthesized, which do not have natural analogues. Synthetic zeolites are typical examples of synthetic minerals utilized in various industrial applications, because of their high cation exchange capacity, their catalytic properties and their action as molecular sieves due to the presence of channels of certain dimensions in their structure. They are preferred by the chemical industry over the natural zeolites, because they have a concistent and homogeneous composition. Moreover novel species with superior properties have been synthesized, which do not have natural analogues (i.e. zeolite A, zeolite ZSM-5 ect).

Although synthetic zeolites have prevailed over their natural counterparts in the chemical industry, natural zeolites are also used successfully in several applications, mainly in environmental protection, in agriculture, in aquaculture, in animal nutrition and as a building stone (Holmes, 1994). Similarly, both synthetic and natural diamonds are utilized by the abrasives ndustry and natural and synthetic smectites compete in many applications. A well known synthetic trioctahedral smectite is laponite (synthetic hectorite) which has very important gelling properties. In other cases, synthetic minerals have replaced natural ones almost completely from their main application field. For example emery has been replaced by synthetic materials in most markets for abrasives. It now finds applications only in non-skid flooring and concrete hardening, which consume only small amounts (Holroyd & McCracken, 1994).

2.4 Variable functions in industry

Industrial minerals and rocks and the products derived from them are interrelated in various industrial processes. The interdependence has three components. a) Use of raw materials or their products for production of another industrial mineral b) synergetic action of different industrial rocks or minerals in an industrial application and c) complementary action of different industrial minerals in industrial applications. Typical example in the former case is the production of sulphur with the Frasch process (Bates, 1969). Production of sulphur with the Frasch process requires large quantities of fresh water, which are filtered and treated by chemical compounds such as anhydrous disodium phosphate, lime and hydrated dolomitic lime sodium hydroxide, sodium carbonate sodium nitrate etc. These compounds are produced from other industrial minerals, including limestone, dolomite, sodium chloride (halite), and phosphorite. Examples from the latter case are the iron and steel industry and the drilling industries. The iron and steel industry utilizes a large variety of industrial rocks and minerals in different stages of production. Moulding sands are made of quartz, chromite, olivine or zircon grains bound by bentonite, fluxes may contain limestone, dolomite, lime or fluorspar, and refractory bricks are made of magnesite, dolomite, alumina silica or mullite. Also the drilling industry utilizes bentonite and barite to lubricate the drilling bit and stabilize the drilling fluids. These industries are totally dependent on the use of industrial minerals.

2.5 Specifications and standards

Assessment of an industrial rock or mineral often involves comparison of the physical or chemical properties of the raw material or the processed end product with certain national or international standards which have been issued by national or international institutions (ASTM, BSI, DIN, API, OCMA etc). This is not the case in ore deposits in which only the grade of the ore or the mineral concentrate is examined by the end user. In some cases the specifications for the property in question is dictated by the end user. In this case the end user often invents a specific test which is adopted by other industrial users. For example the suitability of industrial minerals as animal litters is examined by the Westinghouse test, which has been proposed by an industrial user (Jaffee *et al.,* 1992).

Often industrial minerals or rocks with superior physical properties, which could meet specifications and would therefore have high unit value, are utilized as low unit value raw materials. In this case the raw materials are *underutilized.* This is due to a) the limited development of industry in the country, which could utilize the raw material to gain maximum benefit or b) to the existence of alternative industrial minerals which act as substitutes of a raw material. The former is very common in carbonate rocks, both limestones and dolomites. In this case carbonates are utilized mainly as aggregates with low unit value, although they may have white colour or may be chemically pure to be used as fillers or in the chemical industry. This is because, either there are not industrial users for the raw material, or there are technological constraints (e.g. use of acid technology in the paper industry requires kaolin fillers instead of calcite fillers). The latter is common in countries with deposits of different industrial minerals, which can be used in common applications, such as dolomite and magnesite. For example Greece is a country with significant reserves of pure dolomites and good quality cryptocrystalline magnesite deposits. Mining companies do not extract dolomite for refractory use because a) the tradition is to use magnesite as long as there are sufficient reserves and b) the limited iron and steel industry in the country which would require additional refractory resources

3 Environmental constraints and waste products

The public demand and associated legislation to protect the environment is a constraint on mining activity in most European countries and the US. With a few exceptions (e.g. asbestos, Si-rich minerals, Fe-oxides, manganese ores), industrial minerals and rocks are usually non-hazardous in normal usage. The environmental impact of exploitation and processing of industrial minerals and rocks is associated mainly with physical (mainly optical) environmental damage. Dust generation during mining and processing of industrial minerals causes also negative environmental impact. In general, many industrial minerals and rocks are already present in the natural environment. Usually, processing of industrial minerals involves methods which do not emit undesirable by-products except for dust. This is a main difference with ore minerals, in which pollution with heavy metals and/or acid mine drainage is a main concern. As an example, in Northern Greece in Chalkidiki Peninsula currently there is mining activity in magnesite and Pb-Zn deposits. The local communities are opposed against the Pb-Zn mines, but not against the magnesite mines. Nevertheless, there is growing public concern for the environmental impact from mining of industrial minerals. In most European countries land use issues have changed and extension of permits of exploitation is difficult, even for aggregate quarries, although the construction industry is still growing.

Opencast mining changes the landscape in an area.. Mining projects include reliable complete reports on the life cycle both of the minerals and the land use of the mining area, with submission of reliable restoration plans after the cessation of the mining activity. Restoration of old mine sites is more demanding in hard rock quarries. In the past abandoned hard rock quarries are utilized as landfill sites for urban waste disposal. This takes place less often nowadays. The current trend is to return them to local communities for recreation purposes (formation of artificial lakes etc) after amendments. Recreation is more difficult because quarry faces are steep, and plant growing is impossible without transport of soil on the bedrock. In the case of quarries of dimension stone a significant proportion of waste is produced, the management of which is often difficult. Management of waste products is a difficult task in building stone quarries. In some quarries of white marble the waste materials are ground to produce mortars and fillers. The problem of environmental impact is less acute in soft rocks and clays because quarry faces are less steep due to erosion and restoration is easier. Nevertheless, even in the case of soft rocks extraction leaves empty spaces to be filled, or some other after use needs to be found.

Many industrial rocks and minerals find applications in environmental protection, either as adsorbents of inorganic or organic pollutants or because of their impermeability. Typical examples are bentonites and common clays, zeolites, limestone, dolomite and various products from processing such as lime or dolomitic lime. A more interesting environmental aspect is the recycling of various types of waste products from the mining or the metallurgical industry, or the synthesis of high added value industrial minerals from waste materials. Well known examples of recycling of mining waste is the quartz-feldspar-mica waste of the Cornish china clay deposits, UK, and the utilization of blast furnace and steel slag. These waste materials are used as aggregates. Also, the pulverized fly ash (pfa) produced in the coal stations, is utilized in the manufacture of cement. Utilization of mining and metallurgical waste products has a main constraint, related to the frequent lack of markets close to the mining areas. In several cases these areas are located away from main urban centers, making recycling a non-profitable activity. This is the case for the china clay waste in Cornwall, UK, which is used in a local scale.

In some cases waste materials from extraction of industrial rocks and minerals can be recycled and used for synthesis of high added value minerals. For example hydrothermal treatment of fine-grained perlite waste with NaOH solutions at temperatures 90-120 °C yields zeolite NaP, hydroxysodalite, zeolite V, A, or X (Christidis *et al.,* 1999; 2002). Similarly hydrothermal treatment of pulverized fuel ash (pfa) can yield hydroxysodalite, zeolite A and zeolite X (Pool *et al.,* 2000) or K-H zeolite (Mimura *et al.,* 2001), depending on the composition of the hydrothermal solution. Often these wastes are used for back-filling of open quarries after the cessation of mining operations or stored. In this manner optimization of the utilization of industrial mineral resources is achieved via minimization of waste materials, while simultaneously high added value products are synthesized. However, synthesis of high added value products from waste materials may not be feasible a) if the mining industry is not versatile or does not have the technological know-how to perform waste recycling and synthesis of industrial minerals b) if the quantity of produced waste materials is not adequate to sustain synthesis of high added value industrial minerals at industrial scale and c) if there is not market available to consume the synthetic end products.

Lack of operational versatility of a mining company is a main constraint for development of a mineral synthesis circuit in a mining site. The waste materials have very high place value and thus very low unit value; therefore the recycling-synthesis process has to take place at or close to the processing units of the company. The industrial mineral synthesis unit is a completely different plant which requires careful design, additional human and material resources and different management. In fact it is a chemical industrial unit located within a mining processing plant. If the mining company is not willing to perform industrial mineral synthesis, then another industry may undertake the project. In this case the waste materials may be transported away from the production site raising production cost. This drawback is counterbalanced by the very low unit value of the raw waste materials. Note that synthetic zeolites are made by the hydrogel process, which uses expensive starting materials such as silica gel. Finally the possible lack of adequate quantities of starting waste materials may be overcome by use of additional raw materials. For example in zeolite synthesis from fine grained waste materials the lack of adequate waste material can be overcome by use of perlite, which has identical composition.

4. Economic aspects of industrial minerals and rocks

Raw materials have been utilized from ancient times and have contributed to the development of various stages of human civilization. Historical times have been divided into the Neolithic age and the bronze and iron ages according to the composition of the main tools utilized by the man. The construction of important historical monuments which belong to the world cultural heritage like the Egyptian Pyramids the Greek Acropolis or the Roman Coliseum has consumed important industrial rock resources. Also clays were utilized for the manufacture of ceramics as early as the Paleolithic age (Vandiver *et al*., 1989). The development of an economy and civilization based upon manufacturing industry depends on the ability of a country to have access on adequate mineral resources, either indigenous or imported via trading. In historical times after the introduction of metal processing and subsequent utilization, the role of metals was more important than that of industrial rocks and minerals in economy. This was especially the case after the industrial revolution in the mid 18th century in the UK and later in NW Europe and the USA. Since then the role of industrial minerals and rocks has gradually increased and today the value of produced industrial minerals in most developed economies exceeds that of metals.

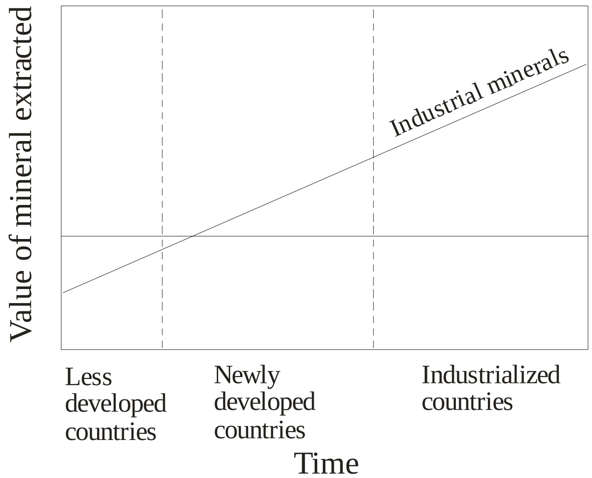

Fig. 1 Schematic diagram depicting the relative value of minerals extracted in various countries (adopted from Bristow, 1987).

The relative importance of metallic or industrial minerals to the economy of the various countries reflects the *economic maturity* of that country (Bristow, 1987). In less well developed countries metallic mineral products dominate over industrial minerals and are predominately exported to industrialized countries. With increasing development the relative importance of industrial minerals for the domestic manufacture increases. According to Bristow (1987), the point at which industrial minerals become more valuable than metals varies among the various countries, reflecting the industrial maturity of each country (Fig. 1). In the UK the change was in the 19^{th} century, in the USA in early 20^{th} century, in Spain in the early seventies and in Australia in the late eighties. In all mature industrialized countries the value of industrial rocks and minerals by far exceeds that of metals (Fig. 1). In Fig. 1 it is noteworthy that the value of metals is considered essentially constant through time.

In industrialized countries a majority of the industrial rocks and minerals extracted are linked to the construction industry (Manning, 1995). These materials include sand and gravel and crushed rock aggregates, (limestone and dolomite, igneous rock, sandstone), silica sand, clays and gypsum. Moreover, limestone and clays are used in the manufacture of cement, which also is consumed in the construction industry. Hence aggregate production depends entirely on the activity of the construction industry. The gradual increase of the value of industrial minerals in developed industrialized countries is related with the vast increase of the construction industry in these countries. This is related to the increasing urbanization and growing housing demands for the population, which migrates from the country to the urban areas and which is related with changes in the use of land. As a test of evidence one of the main economy sectors which have been affected by the recent economic recession is the construction industry, and this has affected adversely the production of aggregates and cement.

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