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Overview of mining residues incorporation in construction materials and barriers for full-scale application

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Highlights

- Tiles, bricks, mortars and aggregates are feasible applications of mining residues
- Mining residues inclusion may improve physico-chemical properties of products
- Geopolymerization is a mechanism to recover mining residues in a safe manner
- Thermal treatment may neutralize mining residues, getting pozzolanic reactivity

Abstract

Resources efficiency regarding the decrease of residues generation and disposal are important steps towards a cleaner production in the construction and mining industry. Minning processes generate huge amounts of residues, and some deposits have accumulated them over hundreds of years, causing environmental and public health problems. However, mining residues can be recovered as secondary supplies for construction materials production due to its physical, chemical and microstructural properties. This study presents a critical review on sustainable strategies researched to introduce mining residues in the construction sector. The gaps and barriers of these strategies and final products are discussed, concerning a safe and sustainable inclusion of mine residues in construction materials production.

Keywords

Construction product; secondary resource; alkaline activation; artificial pozzolan; electroremediation

1. Introduction

The importance of improving building energy performance for saving energy and enhancing construction sustainability has been widely recognized (Sandanayake et al., 2019). Urbanization has become an increasingly critical issue as 55% of the world population lives in urban areas and this figure is predicted to keep growing up to 68% by 2050 (UN, 2018). This scenario will imply a larger consumption of raw materials to produce construction products.

Traditional construction is commonly cement-based, such as concrete and some mortars. Concrete is the second most consumed substance on Earth, after water, and its exploration is one of the main causes of greenhouse gas emissions (Balaji et al., 2017). About 10% of the global emissions of CO_2 are due to construction materials production, where cement accounts approximately for 85% (Kappel et al., 2017).

To revert this negative impact, the European Commission (EC) targeted to reduce construction sector emissions by 90% until 2050 (EC, 2011). A compulsory inclusion of a minimal percentage of residues replacing raw materials on constructions may be a feasible way to achieve EC goals. That means reformulating many construction products, depending on the region and type of applications. Cement contents and raw materials could be fully or partially replaced by secondary resources, turning the construction products eco-friendlier and with lower embodied energy.

In the mining sector, during the extraction of ores and minerals, residues such as extremely fine particles are rejected from the grinding, screening or processing of the raw material. These residues are typically slurried into large impoundments (USEPA, 1985). The reuse of these secondary resources is highly encouraged due to the amount of its generation and the economic and environmental costs associated to its management (EC, 2019). Furthermore, from these residues it may be possible to extract significant contents of (critical) raw minerals particularly from old mine residues that have been explored by aged technologies.

However, mining residues may contain harmful compounds, such as heavy metals that are commonly prone to leach (Candeias et al., 2013). Strategies to remove or neutralize these elements are also important to optimize the use of mining residues with different compositions. The literature dealing with mining residues' incorporation in the production of construction products is diverse in terms of the type of mining residues and its composition. Safe mine residues incorporation to produce construction products can become a key factor for a sustainable construction sector facing primary resources overexploitation, whilst contributing for research and innovation projects to the circular economy strategy empowered by the EC (Gonzalez & Mamalis, 2019).

Climate change is a powerful motor for innovation in the field of raw materials replacement towards an eco-efficient production of construction products. The present work aims at reviewing the existing literature on construction products produced with mine residues, taking into account their physical, chemical and microstructural properties and also economic, social and environmental aspects.

2. Methodology

The research status on mining residues reuse in construction products was performed (January 2020) with the online version of Scopus. With the search words “construction”, “material”, “mining”, “mine wastes”, “tailings” and “residues”, a total of 1,025 scientific papers were obtained from 1969 to 2020 (Figure 1). The dominant research areas were engineering (25.7%), earth and planetary sciences (22.4%) and environmental science (20.6%).

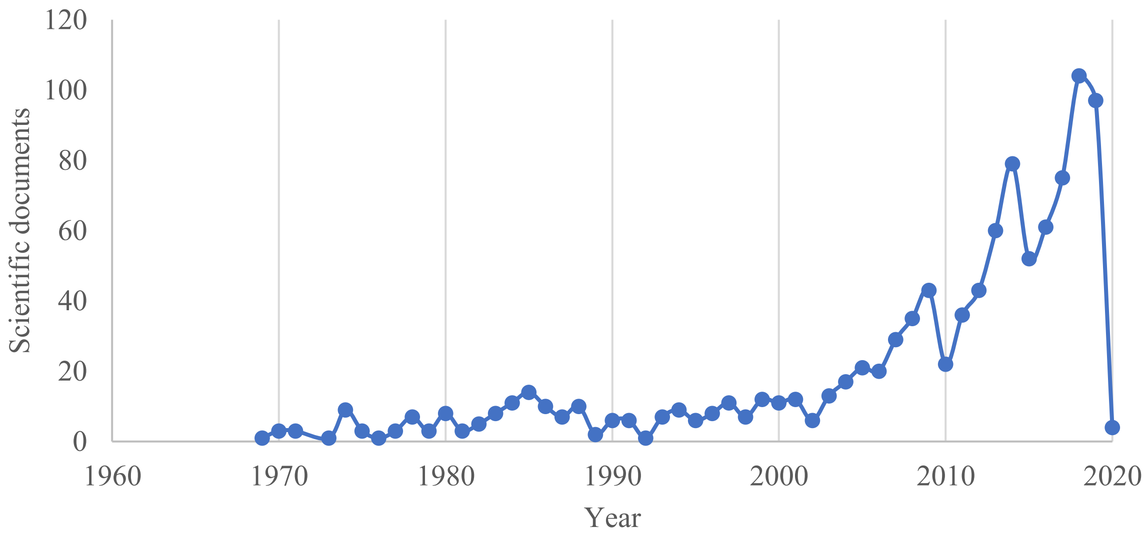

Figure 1. Number of scientific documents by year related to mine residues in the construction materials production - SCOPUS, 2020, accessed in 6.01.2020

This study focuses on analysing the methods of mine residues introduction in the construction industry. The mining residues from different types of mined ores are presented and differentiated as examples of incorporation in the construction sector. Features and drawbacks are presented, as well as environmental impacts of mining residues. The review is based on the available scientific literature.

3. Mining residues properties potential

The generation of rock residues by mining industries has accumulated over centuries into heaps and it is necessary to pursue new economic solutions that can contribute towards their reuse. Lottermoser (2010) estimated that around 20 to 25 billion tons of solid mine residues are produced annually in the world, where 5 to 7 billion tons are fine mine residues (Mudd & Boger, 2013). According to other approximations, this value is up to 14 billion tons and tends to increase in the future due to the higher utilization of low-grade ores (Jones and Boger, 2012).

Mine residues are also composed by particles of crushed rock with particle sizes ranging from 0.01-1.0 mm, but up to 20% clay-sized particles (0.002 mm) can be found (Bjelkevik, 2005). These variations are dependent on sedimentation, site and processing methods. The fine material contains chemicals and metals, which may be environmentally harmful when released in combination with water and air. These tailings can be described in soil mechanical terms and their geotechnical properties can partly be compared to natural materials. Their characteristics can diverge due to variations in origin and processing of the ore and deposition methods. The origin affects the size and the gradation of the grains, the internal friction angle and the particle density (Bjelkevik, 2005). Mine wastes generally have high water content and porosity, low to moderate hydraulic conductivity and low plasticity when compared to soil. The shear strength has usually been rated low to moderate but found to be moderate to high in relation to the grain size compared to natural materials (Bjelkevik, 2005).

Focusing on iron, copper and gold mine residues, different properties can be seen, that affect the durability of a possible construction material produced.

Hu et al. (2017) conducted laboratory experiments to analyse the static and cyclic characteristics of coarse and fine iron and copper tailings. Both coarse mine residues were classified as silty sand (SM) and both fine mine residues were classified as sandy lean clay (CL). Fine mine residues showed larger coefficients of compressibility (0,260 and 0,085 for iron and copper, respectively), lower permeability (void ratios of 1,41 and 1,03 for iron and copper, respectively), lower strength and lower cyclic resistance, compared to coarse mine residues. When comparing iron and copper mine residues, iron mine residues demonstrated to have higher coefficients of compressibility, lower permeability, lower strength and lower cyclic resistance, both for the coarse and fine fractions (Hu et al., 2017).

Properties from gold tailings were investigated by Mapinduzi et al. (2016). These residues have been classified as alkaline silty materials of low plasticity with low organic contents (1.99-2.45%) and nitrogen contents (0.9 - 1.0 mg/kg). The cation exchange capacity range is between 6.0 to 7.5 meq/100 g and is dependent on clay content. The pH varies from 7.2 to 7.5, typical for soils with large amounts of calcium and magnesium. The major oxides present are silica (SiO_2), which form more than 50% w/w, alumina (Al_2O_3) with 9.6 to 14.6% w/w, iron (Fe_2O_3) with 10.4 to 17.5% w/w, and sulphur (SO_3) with 11.4 to 12.1% w/w (Mapinduzi et al., 2016). Silica and alumina are relevant elements for the production of construction products. When submitted to a relatively low thermal treatment, silica and alumina state may change to an amorphous form. The material may acquire pozzolanic reactivity, potentiating the development of different construction products, namely by partial conventional binder replacement.

Only in Europe there are a wide range of mine ores, accounting at least 31 different deposits (Euromines, 2019). Table 1 shows some examples of mine deposits in Europe and their main specificities. Also, for the different ores explored, diverse toxic compounds are identified, such as arsenic, antimony, lead, nitrogen and sulphate. The risks of these elements for the region and for the production of construction products should be carefully addressed since it can compromise the durability of the product, the environment and public health. Nitrogen ending up in the water systems surrounded may cause eutrophication issues. Sulphates may also be accumulated in surface waters compromising water quality. Arsenic and antimony have harmful effects for public health, namely in cardiac and gastric systems, and also for the water ecosystems.

Table 1. Examples of mine deposits in Europe and summary characterization

Mine	Deposit type	Ore explored	Risks identified (compounds)	Reference
Evia, Greece	Epithermal- and porphyry	Nickel and Iron	-	Melfos, 2012
Kiruna, Norrbotten, Lapland, Finland	Magnetite-apatite	Iron	Nitrogen	Nilsson, 2013
Kittilä, Lapland, Finland	Pyrite	Gold	Arsenic, Antimony, Sulphate and Nitrogen	Baciu et al, 2018
Neves Corvo, Beja, Portugal	Volcanogenic massive sulphide (VMS)	Cooper, Lead, Zinc and Silver	Lead	Newall et al, 2017
Panasqueira, Covilhã, Portugal	Wolframite	Tungsten, Tin, Copper	Arsenic	Beghoura, 2017
Polkowice-Sieroszowice, Legnica-Glogów, Poland	Carbonate	Cooper and Silver	-	Załoziński, 2013

Pyhäsalmi, Pyhäjärvi, Finland	Bimodal-felsic	Zinc and Cooper	-	GTK, 2018

4. Construction products produced with mining residues

Mining residues have promised to be a sustainable and efficient alternative source for reuse in the construction sector. There are many studies regarding their application in different construction products and raw materials replacement.

4.1 Alkali activated construction products

The reduced amount of greenhouse gas emissions made alkali activated construction products, also called geopolymers, one of the primary replacements for Portland cement (Ahmari et al., 2012). Geopolymers (Figure 2) are a class of inorganic polymers which have an amorphous structure of $[SiO_4]^{4-}$ and $[AlO_4]^{5-}$, generally produced by mixing a raw aluminosilicate source in the form of a powder with an alkaline silicate solution followed by curing (Romagnoli et al., 2012; Lin et al., 2012). Several aluminosilicate sources are applied for sustainable geopolymers production, such as metakaolin resulting from kaolin thermal treatment to achieve amorphous form (Pacheco-Torgal et al., 2011; Heah, 2012), fly ash (Onisei et al., 2012) and different types of slags and sludges (Pacheco-Torgal, 2007; Yang, 2012).

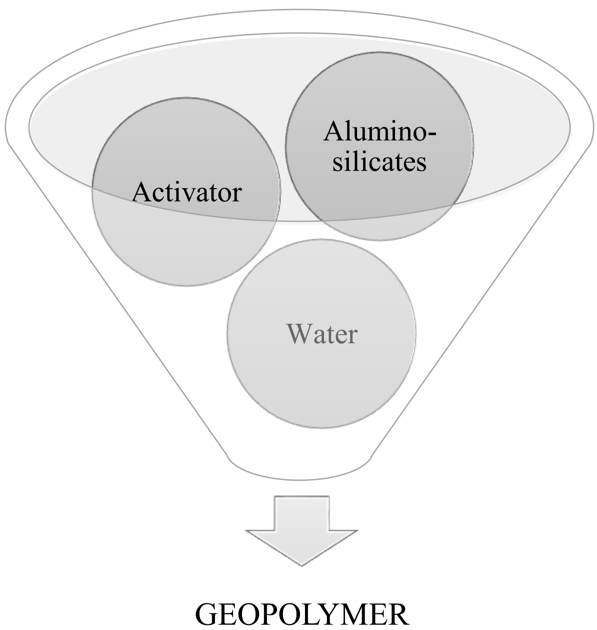

Figure 2. Geopolymers' components for formulations

Research focused on the reuse of residues (mining and quarrying) by integrating them into new construction products manufacture. Numerous works were developed with geopolymerization bases. Table 2 presents examples of mining residues incorporation in geopolymeric construction materials. Geopolymerization of mine wastes is mainly done through alkali-activation, which consists in the addition of a strong base to the mixture. Sodium hydroxide (NaOH) is the principal base selected for this purpose, although other reagents can be applied. (Panias & Giannopoulo, 2007; Ahmari & Zhang, 2012; Chen et al., 2011; Cihangir et al., 2012; Kiventera et al., 2016; Gitari et al., 2018; Beghoura et al., 2017). The main drawback of this technique is the use of reagents, namely strong bases. The replacement for natural products or secondary alternatives would present benefits for the environment.

Table 2. Examples of mining residues in geopolymeric construction materials

Mined ores	Location	Final product/Goal	References
Copper	R.N.Macedonia	Fly ash-based geopolymers	Panias et al. (2007)
Copper	Arizona, USA	Geopolymeric bricks	Ahmari & Zhang (2012)
Iron	Western Hubei, China	Geopolymeric bricks	Chen et al. (2011)
Gold	Finland	Raw material for construction industry	Kiventera et al. (2016)
Gold, Copper	Musina, Limpopo, New Union, South Africa	Aggregates for conventional bulk manufacture	Gitari et al. (2018)
Tungsten	Portugal	Foamed lightweight materials	Beghoura et al. (2017)

The reuse of tungsten mining wastes into innovative alkali-based materials for road pavement applications (Sangiorgi et al., 2016), red clay bricks (Sedira et al., 2018; Gavali et al., 2019) and light weight construction products (Kastiukas et al., 2019) have proof to be a feasible strategy for the construction sector. For local communities, and since the mining sector is not stable along the time, the potential to reuse these secondary sources in different sectors may lead to an increase of the economic and social impact. Also, the durability of the products can be improved with the incorporation of mining residues comparing to the conventional products.

The properties of the final construction products are dependent on the components selection for the mixture and the incorporation rate of each raw material. According to Kiventera et al (2016), when adding commercial granulated blast furnace slag (CGBF) as a co-binder to the alkali-activated tailings, parameters like strength, thermal stability, chemical and fire resistance tend to increase.

However, lower density, micro/nano-porosity and shrinkage are obtained. Resistance to acid and sulphate attack has also been highlighted (Cihangir et al, 2012). The incorporation of mine residues has reached 84% when fly ash is used as additive (Chen et al, 2011).

Beghoura et al. (2017) developed a new alkali-activated binder by reusing mining wastes from Panasqueira tungsten mine, which showed good reactivity with alkaline activators and calcium hydroxide, for high alkali concentrations and curing at room temperature. The improvement on alkali-activation conditions was achieved by mixing mining clay residues with different sources of silica (river sand and amorphous ground glass residues) and cured at moderated temperatures.

The alkaline activation of other aluminosiliceous industrial by-products is known to yield binders, making their properties comparable or stronger and more durable than conventional Portland cement (Castro-Gomes et al., 2012). Cost comparisons show this alkali activated cementitious material is one of the most cost-efficient repair solutions (Pacheco-Torgal et al., 2008). The replacement of Portland cement by new alkali activated binders using mining residues was also studied by several researchers due to its enhanced environmental and durability performance (Pacheco-Torgal et al., 2008; Longhi et al., 2016).

Different combinations of mining sludge residues, grounded glass residues, Portland cement, metakaolin and expanded cork were mixed together with alkaline activators (sodium silicate and sodium hydroxide solution), as well as aluminum powder or hydrogen peroxide to produce foamed lightweight materials. Studies have shown the feasibility to produce improved lightweight foamed alkali activated materials incorporating expanded cork for applications in artistic, architectural, and historical heritage restoration (Beghoura et al., 2017).

Geopolymeric products are now gaining attention, since through the alkaline activation is possible to neutralize different mixtures, with different resources incorporation. In terms of materials properties, it seems they are equivalent or better and with higher durability than conventional Portland cement, what makes this technique promising for the green movement of construction.

4.2 New-polymer based construction materials

The development of innovative polymer-based composite materials obtained from non-contaminated mine residues was also found an important strategy in the literature review. There is mechanical and physical potential for the reuse of Panasqueira aged rock-residues as new polymer-based construction materials in several applications (Castro-Gomes et al., 2012). These materials have shown great potential for conservation, restoration and/or rehabilitation of historic monuments, sculptures, decorative and architectural intervention or as materials for building coatings (Castro-Gomes et al., 2012).

Different added value applications for reusing mining and quarrying residues are the production of compact composites, namely from marble or quartz residues. Compact composite products can be constituted by several sizes of particles/aggregates linked by a polymeric resin matrix. This aggregate/polyester matrix is optimized for mechanical and durability properties. The economic value of such composites depends principally on its aesthetic appeal (textures and colour scales) (Peralbo Cano, 2007).

This is an innovative approach for reusing mining residues, as proposed by Peralbo Cano (2007), where new applications were developed for architectural, technical-sculptural and restoration process, by reusing residues of quarrying industry of Macael region, Spain. Different types of polymer-based mortars were produced incorporating fine residues, from dust to sand sized particles. Mortar properties and its potential for industrial applications is dependent on the texture and white colour scale of the residues (Peralbo Cano, 2007).

It is possible to modify the original colours of natural quartz adding colour pigments and other compounds that confer high durability, resistance and consistency. The result is a large variety of designs, formats and finishes. Such advanced composite materials are compacted under intense vibration, vacuum, and pressure, resulting in dense and nonporous panels. Their appearance and properties differ according to the raw materials used. Besides quartz or granite, marble is also used in such composites, which can additionally incorporate residues from mining and quarrying industries (Castro-Gomes et al., 2012).

New-polymer based products showed a great potential to provide personalized and original products for different purposes. The addition of different pigments makes possible to change the colour and also confer high durability to the products.

4.3 Ceramic tiles

Das et al. (2000) described a sustainable way of handling iron ore tailings by converting them into ceramic floor and wall tiles for building applications. The iron ore tailings were found to contain high percentage of silica and could be used up to 40% (by weight) as part of raw materials for ceramic floor and wall tiles production. Ceramic tiles from iron ore tailings were found to be superior in terms of scratch hardness and strength, while also keeping the essential properties of ceramic tiles made from conventional raw materials (Das et al., 2000).

Amorphized tungsten tailings after magnetic separation demonstrated to have proper crystal structure and high performance to produce ceramic tiles. The gehlenite–hedenbergite glass ceramics repaired from tungsten mining wastes by controlled crystallization showed great potential (Peng et al., 2014).

The wastes from mining of boron-rich minerals, basalt rock and recycled soda-lime glass can be modified into a new product, between traditional ceramics and glass–ceramics, by using direct sintering at 1050 °C for only 30 min (Cetin et al., 2015). The surface porosity of the glass–ceramic body can be sealed by a glass–ceramic glaze, produced from the same starting mixture of residues and minerals (Cetin et al., 2015).

Ceramic tiles can be produced in a superior way taking advantage of tailings, namely with iron, due to its colour (red-orange) and other chemical and physical properties.

4.4 Bricks

Several studies have shown the potential of mine residues to produce bricks in a more sustainable way. The possibility of applying tailings from Kolar Gold Fields, Karnataka, for brick fabrication was assessed by Roy et al. (2007). Since plasticity index of the tailings is zero it cannot be used directly for brick production. Thus, some additives that had plasticity or binding properties, such as Portland cement, black cotton soils and red soils were tested in the mixture with tailings from Kolar Gold Fields. According to the additives used, the bricks were termed as cement-tailing bricks or soil-tailing bricks. Bricks with 20% of cement and 14 days of curing were found to have suitable properties in terms of linear shrinkage, water absorption and compressive strength (Roy et al., 2007). Also, bricks with high mechanical strength were produced with mine wastes from Jerada, Marocco (Taha et al., 2016; Loutou et al., 2019).

Several works focused on iron ore mine residues incorporation to produce bricks. Different mixtures were carried out, adding to the mine residues components like soil, sand, cement, fly ash, gypsum and/or lime. The properties of the final product, such as compressive strength and water absorption, were found suitable for building products (Ullas et al., 2010; Muduli et al., 2010; Yongliang et al., 2011; Zhao et al., 2012; Jemishkumar et al., 2014; Diaz-Loya et al., 2019).

Studies demonstrated that iron ore residues can be also applied as aggregate in manufacturing of non-fired bricks, such as adobe, extruded or compacted earth bricks (respectively EEB and CEB), having a clear advantage in terms of low embodied energy products. However, as the incorporation of the residues reduces plasticity of the brick's mixture before moulding, for adobe and EEB may be a drawback since plasticity is an important factor. Therefore, additives such as mineral binders may be needed to improve its plasticity.

4.5 Aggregates for pavements and concrete

Aggregates are materials commonly applied in several products of the construction sector. Mine residues have been studied to partially replace raw aggregates in road pavement applications showing they have compatible physical properties (FHWA, 2016) and, therefore, presenting great potential for this application (Amrani et al., 2019).

Hot mix asphalt (HMA) was developed containing mining waste as aggregates for making medium to low traffic roads. Kota stone was used to make bituminous concrete (BC) and dense bituminous macadam (DBM), replacing conventional basalt aggregates. Up to 50% replacement of conventional stone in BC mixes and 25% in DBM show satisfactory results for moisture susceptibility, resistance to rutting and low cracking temperature (Gautam et al, 2018).

A lightweight aggregate was produced by sintering a mixture of Korean gold mine tailings, red mud and limestone (Jung Ju et al., 2017). However, the abrasion loss value of the aggregate was 290 mg, which exceeds the limit of 200 mg required in Korea. Heavy metals did not leach from the aggregate, despite the significant amounts of lead, arsenic and fluor existing in the residues. Although harmful elements present in the mine residues did not leach, other sources of pollution should also be assessed. The air indoor quality is also an important parameter since some elements can volatilize causing risks for the users.

The skid resistance and bond strength, together with physical properties of the reconstructed aggregate of the gold mine tailings were appropriate for use in bicycle lane construction, although the dissolution of calcium and the pH level of the leachate need to be controlled to protect aquatic ecosystems (Jung Ju et al., 2017). This will imply a hard and straight monitoring process, before, during and after the production, what in terms of costs could not compensate comparing to the conventional methods of aggregates production. Thus, the cost-benefit analysis is very important to support the feasibility of the mine residues incorporation in those cases.

Construction aggregates were also produced from a gold mine in Abitibi-Temiscamingue region, Quebec, Canada (Benarchid et al, 2018). Rock residues samples containing 46% of coarse material have similar properties to common concrete. Depending on its composition, gold mine waste rocks show potential to replace almost 50% of the concrete needed, with a strong impact in an industrial scale.

Huang et al. (2007) produced artificial lightweight aggregate (LWA) manufactured from recycled resources (mining waste, fly ash from an incinerator and heavy metal sludge from an electronic wastewater plant). LWA produced by sintering in tunnel kiln shows good vitrified surface, low water absorption rate (below 5%), and low cylindrical compressive strength (4.3 MPa). In addition, the study reported that only trace amounts of heavy metals were detected (Huang et al., 2007).

The presence of heavy metals is a parameter that authors are not addressing deeply. Although authors are awarded of the presence of harmful elements in the residues and, probably, in the materials formulated with them, no further tests show its influence in the surrounded ecosystems. If there are heavy metals, the monitoring process should be included since weather conditions and many other factors may influence its release in the atmosphere, apart from the influence on construction materials properties.

The use of mine tailings from a lead-zinc mine as a partial aggregate replacement in self-compacting concrete was also assessed (Janković et al., 2015). The mine residues have no pozzolanic activity and their application in mortar and concrete can be made in the form of replacement of a certain percentage of aggregates. The results show that concretes with addition of 10% and 20% of mine residues achieved higher strengths when compared to a conventional concrete with 28 curing days.

Iron ore tailings may be used for complete replacement of conventional aggregates in concrete. An iron ore tailings aggregates concrete exhibited good mechanical properties, showing a compressive strength 12% greater than a conventional aggregates concrete (Kuranchie et al., 2015). However, due to the high content of fines in residues' aggregates, the indirect tensile strength is not superior when compared to the conventional concrete production.

Iron ore tailings were also tested to replace river sand in concrete (Shettima et al., 2016). Test results with 25%, 50%, 75% and 100% of replacement indicated that concrete workability was poorer, but strength and modulus of elasticity were consistently higher than for conventional concrete.

With the incorporation of mine residues for aggregates production and concrete aggregate replacement it is possible to improve properties as deformability and compressive strength. However, the workability may be affected. Also, the presence of heavy metals and other harmful compounds will imply the need of a straight monitoring process, since many factors may influence leaching and other release ways to the environment.

4.6 Mortars

Mortars are one of the most common construction products and can be constituted by only one or more types of mineral binders and aggregates. Mortars can also include additions, like pozzolans or fillers, and admixtures, such as plasticizers, in their formulation (Grilo et al., 2014; Paiva et al., 2017). In this sense, mortars were also subjected to mining residues incorporation in several studies. Mortars are frequently studied instead of concrete since they constitute a concrete matrix without the coarser aggregates (Table 3).

Table 3. Examples of mining resources applications in mortars production and purposes

Mining resource in mortar formulation	Purpose	References
Tungsten residues powders/tailings	Binder replacement	Peng et al. (2005); Choi et al. (2009)
Iron mine residues	Aggregate/Binder replacement	Hao et al. (2013); Fontes et al. (2016)

Gold mine tailings	Additive	Kunt et al. (2015); Taha et al. (2019); Sigvardsen et al. (2018)
Bauxite mine residues	Binder replacement	Ribeiro et al. (2013)
Copper tailings	Aggregate replacement	Pavez et al. (2016); Sigvardsen et al. (2018)
Barite-fluorspar mine waste	Additive/Aggregate replacement	Gallala et al. (2017)

Peng et al. (2005) applied tungsten residues powders, activated by mechanical and chemical methods, as cementitious material in mortars. Garnet was the major group of silicate minerals present in the mine residues, which improved chemical and structural stability of the final mortar (Peng et al., 2005).

Conventional material for cement mortars was also replaced by tailings from a tungsten mine in Sangdong, Korea (Choi et al, 2009). This technique was effective for stabilizing and solidifying heavy metals, particularly when used with commercial granulated blast furnace slag. This combination demonstrated acceptable properties for residues volumes up to 10% by mass.

Iron mine residues were used to replace river sand as the adhesive mortar aggregate in the study of Hao et al. (2013). The results show that polymer–cement ratio and cement-mine residues ratio are important factors to the performance of the adhesive mortar. The adhesive strength did not decrease with the incorporation of the mine residues (Hao et al., 2013)

Kunt et al. (2015) studied the potential of Bergama gold mine tailings (Turkey) as an additive in mortars. Cement mortars were prepared with a mixture of Portland cement and dried gold tailings. According to the results, mine residues are suitable for mortar production, with an optimum gold mine residues incorporation mass ratio of 5%. Also, several studies reported that heavy metals and metalloids from gold mine waste may be immobilized in the concrete matrix (Taha et al., 2019).

Fontes et al. (2016) evaluated the technical feasibility of using iron ore mine tailings as construction material, for masonry layering, plastering and rendering mortars. Three types of mortars were produced: hydraulic lime conventional mortars, mortars with complete replacement of natural aggregate by mine tailings and mortars replacing the lime by mine residues in proportions from 10% to 100%. Mortars with iron ore mine residues show an increment in the content of mixing water, reduced levels of incorporated air, increased bulk density and improvement of mechanical properties when compared to conventional mortars (Fontes et al., 2016).

Also, Ribeiro et al. (2013) proved that up to 20% of red mud, from bauxite ore extraction to produce alumina, can be used as a cement substitute in mortars. In a calcination range of 450ºC and 650ºC, the red mud provides an acceleration of the hydration process while the workability decrease.
A technical comparison between stucco mortars (gypsum as binder) prepared with crushed conventional sand and with copper tailings was also carried out (Pavez et al., 2016). The best results were achieved for the stucco mortars containing mine tailings. The values of compressive strength (~14.7 N/mm^2), water retentivity (87%), and adherence (0.07 N/mm^2) in the stucco mortars prepared with copper tailings after 28 curing days improved in comparison to the values obtained with crushed sand (~0.57 N/mm^2, 62% and 0.02 N/mm^2, respectively). Therefore, the preparation of stucco mortars using copper tailings replacing conventional sand seems a feasible alternative for the construction industry. In addition, gypsum requires low temperatures for production, making this combination a very sustainable approach for plastering mortars production. Gypsum-based materials are commonly used for conservation and retrofitting projects (Faria et al., 2008).
Incorporation of barite-fluorspar mine waste (BFMW) as a fine aggregate additive has been investigated by Gallala et al. (2017) for its effect on the mechanical and shielding properties of cement-based mortars. Several mortar mixtures were prepared with different proportions of BFMW ranging from 0 to 30% as fine aggregate replacement. The results revealed that mortar mixtures containing 25% BFMW reached the highest compressive strength values, which exceeded 50 MPa. The use of BFMW aggregates increased attenuation coefficient by around 20% (Gallala et al., 2017). Mining residues can be used as partial replacement aggregate to improve radiation shielding and to reduce mortar (and concrete) costs.
Additionally, focusing on the use of mine tailings as a partial cement replacement, residues from Zinkgruvan (Sweden) and Nalunaq (Greenland) presented potential for partial cement replacement (5 and 10%) in cementitious mortars and showed indications of pozzolanic activity (Sigvardsen et al., 2018).
Therefore, the use of mine residues in mortars seems to be promised. The formulations may require the addition of additives (such as GBFS) that may help to immobilize the harmful elements, avoiding leaching phenomena and other contamination problems. At the same time, additives may also improve materials structural and chemical properties. Some mineral groups present in the mine residues may also potentiated the chemical and structural stability (e.g. garnet). However, some studies reported only an optimal replacement ratio of cement by mine residues of 5% by mass. Nevertheless, in an industrial scale, even only 5% will promote significant savings in raw materials for cement production and costs. Furthermore, this percentage may increase replacing fine aggregates by mine residues together with new techniques and strategies to make these residues

more suitable for mortars. This will promote not only a drastic reduction of mine residues disposal but also will make countries less dependent of cement and energetic sources.

5. Environmental and social impacts of mining

As previously mentioned, mining activities affect the environment and associated biota through removal of vegetation and topsoil, displacement of fauna, release of pollutants and generation of noise (Müezzinoğlu, 2003). Furthermore, the management of mining waste that are generated in the mining processes increase the negative impacts. Thus, finding ways to reuse this secondary source in order to reduce mine residues disposal is an important current issue.

The major impact of mining activities is related to water quality and availability in the area (Zhang et al, 2019). The potential for acid mine drainage is an important factor. When the walls of open pits and underground mines, mining residues, rock residues, and heap and dump leach materials are quarried and exposed to oxygen and water, acids can be formed. Acid formation occurs if iron sulphide minerals (e.g. pyrite) are abundant and if there are no neutralizing compounds (Evangelou & Zhang, 1995). Therefore, acids are prone to leach or dissolve metals and other harmful compounds present, forming acid solutions with high contents of sulphate and metals (e.g. cadmium, copper, lead, zinc, arsenic) (ELaw, 2010; Oluwasola et al, 2014).

Mineralogy is important for the ability of residues to neutralize acidity produced by sulphide oxidation. Iron carbonates in the form of siderite, ferroan dolomite and ankerite are less reactive and ultimately provide no net neutralization from the iron fraction of the carbonate due to subsequent Fe hydrolysis under oxidizing conditions. Whereas dissolution of other non-carbonate minerals (primarily silicates and aluminosilicates) can also provide some neutralization of acidic waters, the importance of such minerals in acid-generating environments is limited by low reaction rates (Jamieson et al., 2015).

Toxic constituents can leach even if acidic conditions are not present (e.g. arsenic, selenium, and metals). Elevated levels of cyanide and nitrogen compounds have been found in waters at mine sites, from heap leaching and blasting (Müezzinoğlu, 2003). The impacts of wet mine residues impoundments can include contamination of water, since toxic substances can leach from these facilities, percolate through the ground and contaminate groundwater. Particulate matter from excavations, transportation of materials and stockpiles, may be transported by the wind. Emissions from cars, trucks and equipment increase the particulate levels (ELaw, 2010).

The use of mining residues as construction materials for the production of construction products must comply with the requirements of safety at work during production and transport (Bandow et al., 2017)

In an industrial scale, this aspect is crucial for the inclusion of mining residues in a safe and legal manner, although it has been rarely studied. Furthermore, safety during the lifetime of the construction product may be quite relevant, depending on the application. The construction product can be left exposed (uncoated) or applied as an intermediate layer. Also, depending if the final product will be applied indoors or outdoors, other interventions may be needed.

Construction products are in contact with several environments during their lifetime and, as a consequence of their contents, may release potentially harmful compounds (Bandow et al., 2017). Nevertheless, few studies have addressed this aspect when focusing on the development of construction products with the mining residues.

6. Discussion and research perspectives

Conventional construction products manufacture is under increasing pressure since the primary resources used have a strong impact for the sustainability of this sector. Thus, the use of alternative secondary resources appears to offer a promising way of alleviating this problem.

The industry workers' safety when handling with mining residues to produce construction products and the eventual toxicity of the residues may be one of the difficulties that companies face when considering the incorporation of mining residues in the production of construction materials.

However, broad types of mine residues have shown great potential for construction materials production. A common strategy applied is the previously mentioned alkali activation, such as geopolymerization. This strategy provides materials with suitable chemical and structural properties. Also, geopolymerization may be a key factor to stabilize hazardous compounds in mixtures with mining residues, avoiding leaching problems. This technique seems to be promising in Europe from an environmental, technical and economic perspective. However, although in-depth studied currently, commercially available geopolymeric products are still scarce.

Secondary resources may have latent pozzolanic reactivity (Pontes et al., 2013). A thermal treatment of mine residues may enrich their pozzolanic reactivity. After the thermal treatment, mine residues may be applied as a binder partial replacement for mortars and concretes, or for bricks production. Simultaneously, this process may be proficient to immobilize harmful compounds, preventing toxic risks for the environment. Further research on this topic should be addressed in order to expanse the application of mine residues in the construction field.

Mine residues have also the possibility to be reused from a secondary ore extraction. Since the EC identified 27 critical raw materials with high economic relevance and in risk of scarcity, alternative sources to recover are now being explored (EC, 2017). Various estimations of potential recovery of certain materials compared to their current demand have been done. (Blengini et al., 2019). Thus, the application of a treatment before mine residues reuse could provide the recovery of critical raw materials and the removal or immobilization of harmful compounds, what would be advantageous in terms of economic and environmental perspectives.

Electroremediation has been studied for a wide range of liquid and solid environmental matrices to remove organic and inorganic contaminants. In the electroremediation process (Figure 3), a low-level direct current is applied in a system with charged elements to remove the pollutants (Ribeiro and Rodriguez-Maroto, 2006).

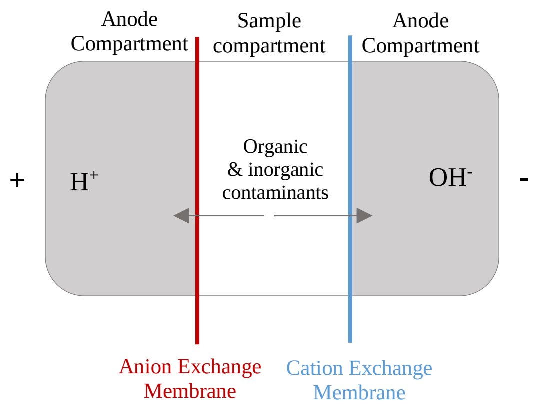

Figure 3. Electrodialytic cell with 3 compartments

In the construction field, electroremediation proved to be an efficient pre-treatment for immobilization of heavy metals in solid environmental matrices and improvement of physical and chemical properties (Magro et al, 2016: Chen et al., 2017; Kappel et al, 2017a; Kirkelund et al., 2019) and to remove salts in liquid environmental matrices (Magro et al, 2018), for matrices reuse in mortar production (Kappel et al, 2018; Magro et al, 2019).

Other strategies, as desulphurization (oxidation of sulphide minerals in the presence of a sulphide activator) have shown potential to reduce the sulphide content from mine tailings (Nadeif et al., 2019). The pre-treatment of mining residues with this technique may be also an important step for a greener incorporation of mine residues in construction materials. Also, it may lead to chemical, physical and microstructural changes that may improve the final material and promote a higher ratio of mineral binder replacement.

Metal ore processing activities generate significant quantities of residues at mining sites, causing environmental issues. The application of mining residues for the production of construction products is considered to be a key factor for the conservation of natural resources and reduction of environmental impacts, both for mining and construction industries. Incorporation of mining residues in construction products should provide competitive products, decreasing costs, resources consumption and mine residues discharge. At the same time, greener management of residues and production of construction products with lower embodied energy should be achieved. It is important to keep intensifying research in this topic in order to implement and improve optimized applications of mining residues in the construction field.

However, recovery processes can be highly energy dependent. Thus, environmental and land use aspects are also important to be considered. Availability of data and information on secondary materials and legislative framework within the EC is essential for the large-scale development of recovery practices (Blengini et al., 2019). Also, the development of a tool to assess climate protection and resources efficiencies, through indicators, will pursue the empowerment of innovative alternatives (Sameer and Bringezu, 2019).

The valorization of tailings in the mining industry is slowly starting. One of the reasons is due to the limited knowledge of its contents and amounts. However, it is mandatory that this situation changes. In a circular economy perspective, the drawbacks related to the way that waste is managed and the conscience of industries to understand the potential of tailings as important and available materials are key factors to change from a linear economy model (take-make-use-dispose). This may promote the development of new business areas. Also, the implementation of taxation might change the profits, empowering the circular economy principles (Kinnunen and Kaksonen, 2019).

The comparative overview of the reviewed papers called up several promising prospects for future research. In this sense, a SWOT (strengths, weaknesses, opportunities and threats) analysis of the mining residues application in the construction sector is presented (Table 4).

Table 4. SWOT analysis of mining residues application in the construction sector

STRENGHTS	WEAKNESSES
⇒ Huge mineral resources availability ⇒ Reduction of mining residues disposal ⇒ Reduction of primary resources exploration ⇒ Sample pre-treatment may not be necessary, depending on residues composition	⇒ Scale-up underdevelopment ⇒ Complex matrix may influence the replicability ⇒ Leaching of heavy metals or other harmful compounds may occur ⇒ An additional step can be needed for some residues: removal or immobilization of harmful elements ⇒ Additives may be necessary to enhance materials properties
OPPORTUNITIES	THREATS

⇒ Green methods development ⇒ Innovation in the construction sector ⇒ Increase knowledge on mining residues handling and products toxicity ⇒ Development of different products and application depending on their eventual toxicity ⇒ Critical raw materials recovery and harmful compound removal strategies from secondary resources	⇒ Percentage of raw materials replacement may not be significative in some cases ⇒ Heterogeneity of the mine residues may influence the results and limit industrial use ⇒ Importation and exportation of residues ⇒ Local politics ⇒ Residues classification and application constraints

7. Conclusions

The incorporation of mining residues into construction products manufacture can decrease consumption of primary resources in the construction sector, as well as improvements on the final products properties without high investments. While current research has been mostly focusing on energy-efficient construction products, residues minimization and reuse strikes as equally important in a context of primary resources scarcity. Thus, based on a literature review and showing several research examples of construction materials and products with mining residues, some gaps were presented, together with barriers that exist in the current literature. The diversity of available mine residues resources around the world, with specific problems, should be considered in further research. Nevertheless, it is clear the potential mine residues reuse can have to enhance eco-efficient construction materials and products.

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References

Ahmari S, Ren X, Toufigh V, Zhang L, Production of geopolymeric binder from blended waste concrete powder and fly ash, Construction and Building Materials 35:718–729 (2012). DOI:10.1016/j.conbuildmat.2012.04.044

Ahmari S, Zhang L, Production of eco-friendly bricks from copper mine tailings through geopolymerization, Construction and Building Materials 29: 323-331 (2012). DOI:10.1016/j.conbuildmat.2011.10.048

Baciu C, Lazăr L, Cozma A, Olenici A, Pop IC, Roba C, et al., Environmental risk assessment practices and applications for gold mines in EU: Assessing environmental risks at three mine sites: Kittilä mine in Finland and Roșia Montană and Zlatna mines in Romania. ERA-MIN – SUSMIN Project Deliverable D5.4 (2018)

Balaji M, Dhilip SS Vigneshwaran A, Fayaz KA, Experimental study on the behavior of self compacting self cured concrete using chemical admixtures and metakaolin (2017). International Conference on Emerging Trends in Engineering, Science and Sustainable Technology (ICETSST-2017)

Bandow N, Gartiser S, Ilvonen O, Schoknecht U, Evaluation of the impact of construction products on the environment by leaching of possibly hazardous substances, Environmental Sciences Europe 30:14(2014). DOI: 10.1186/s12302-018-0144-2

Beghoura I, Castro-Gomes J, Ihsan H,Estrada N, Feasibility of alkali-activated mining waste foamed materials incorporating expanded granulated cork, Mining Science 24:7-28 (2017). DOI: 10.5277/msc172401

Benarchid Y, Taha Y, Argane R, Benzaazoua M, Application of Quebec recycling guidelines to assess the use feasibility of waste rocks as construction aggregates, 10th ACI/RILEM International Conference on Cementitious Materials and Alternative Binders for Sustainable Concrete, Montreal (2018)

Blengini GA, Mathieux F, Mancini L, Nyberg M, Viegas, HM et al., Recovery of critical and other raw materials from mining waste and landfills: State of play on existing practices, EUR 29744 EN, Joint Research Center Science for Policy Report, Publications Office of the European Union, Luxembourg (2019). DOI:10.2760/600775

Bjelkevik A, Stability of tailings dams-Focus on water cover closure, Licentiate thesis, Luleå University of Technology (2005)

Candeias C, Melo R, Ávila P, Silva E, Salgueiro A, Teixeira J, Heavy metal pollution in mine-soil-plant system in S. Francisco de Assis - Panasqueira mine (Portugal), Applied Geochemistry jornal, 44:12-26 (2013). DOI:10.1016/j.apgeochem.2013.07.009

Castro-Gomes JP, Silva AP, Cano RP, Suarez JD, Albuquerque A, Potential for reuse of tungsten mining waste-rock in technical-artistic value added products, Journal of Cleaner Production 25: 34-41 (2012). DOI:10.1016/j.jclepro.2011.11.064

Cetin S, Marangoni M, Bernardo E, Lightweight glass–ceramic tiles from the sintering of mining tailings, Ceramics International 41:5294:5300 (2015). DOI:10.1016/j.ceramint.2014.12.049

Chen Y, Zhang Y, Chen T, Zhao Y, Bao S, Preparation of eco-friendly construction bricks from hematite tailings, Construction and building materials 25 (4): 2107-2111 (2011). DOI: 10.1016/j.conbuildmat.2010.11.025

Chen W, Klupsch E, Kirkelund GM, Jensen PE, Ottosen LM, Dias-Ferreira C, Recycling of MSWI fly ash in clay bricks-effect of washing and electrodialytic treatment. In: WASTES – Solutions, Treatments and Opportunities II. Taylor & Francis, pp. 183-189, 4th International Conference WASTES, Porto, Portugal, 25/09/2017 (2017)

Choi YW, Kim YJ, Choi O, Lee KM, Lachemi M, Utilization of tailings from tungsten mine waste as a substitution material for cement, Construction and Building Materials 23(7): 2481-2486 (2009). DOI:10.1016/j.conbuildmat.2009.02.006

Cihangir F, Ercikdi B, Kesimal A, Turan A, Deveci hUtilisation of alkali-activated blast furnace slag in paste backfill of high-sulphide mill tailings: Effect of binder type and dosage, Minerals Engineering 30: 33-43 (2012). DOI:10.1016/j.mineng.2012.01.009

Das SK, Kumar S, Ramachandrarao P, Exploitation of iron ore tailings for the development of ceramic tiles. Waste Management 20(8): 725–729 (2000). DOI: 10.1016/S0956-053X(00)00034-9

Diaz-Loya I, Juenger M, Serai S, Minkara R, Extending supplementary cementitious material resources: Reclaimed and remediated fly ash and natural pozzolans, Cement and Concrete Composites 101: 44-51 (2019). DOI:10.1016/j.cemconcomp.2017.06.011

EC-European Commission, Final. Communication from the Commission to the European Parliament. Reducing greenhouse gases: a roadmap for 2050, COM (2011) 112 final, Brussels

EC-European Commission, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the 2017 List of Critical Raw Materials for the EU, Brussels (2017)

EC-European Commission, Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on the Implementation of the Circular Economy Action Plan, COM (2019)190 final, Brussels

ELaw – Environmental Law Alliance Worldwide, Guidebook for Evaluating Mining Project EIAs, Chapter 1 (July 2010)

Euromines, Main Mineral Deposits of Europe (2019). Access in http://www.euromines.org/mining-europe/main-mineral-deposits-europe at 11-02-2019.

Evangelou VP, Zhang YL, A review: Pyrite oxidation mechanisms and acid mine drainage prevention, Critical Reviews in Environmental Science and Technology, 25(2):141–199 (1995). DOI:10.1080/10643389509388477

Faria P, Henriques F, Rato V, Comparative evaluation of aerial lime mortars for architectural conservation. Journal of Cultural Heritage 9 (3):338-346 (2008). DOI: 10.1016/j.culher.2008.03.003

Fontes WC, Mendes JC, Silva SN, Peixoto RAF, Mortars for laying and coating produced with iron ore tailings from tailing dams, Construction and Building Materials 112:988-995 (2016). DOI:10.1016/j.conbuildmat.2016.03.027

Gallala W, Hayouni Y, Gaied ME, Fusci M, Alsaied J, Bailey K, Bourham M, Mechanical and radiation shielding properties of mortars with additive fine aggregate mine waste, Annals of Nuclear Energy, 101:600–606 (2017). DOI:10.1016/j.anucene.2016.11.022

Gautam PK, Kalla P, Nagar R, Agrawal R, Jethoo AS, Laboratory investigations on hot mix asphalt containing mining waste as aggregates, Construction and Building Materials 168: 143-152 (2018). DOI: 10.1016/j.conbuildmat.2018.02.115

Gavali H, Bras A, Faria P, Ralegaonkar R, Development of sustainable alkali-activated bricks using industrial wastes, Construction and Building Materials 215: 180–191 (2018). DOI: 10.1016/j.conbuildmat.2019.04.152

Gitari MW, Akinyemi AS, Thobakgale R, Ngoejana PC, Ramugondo L, Matidza M, Mhlongo SE, Dacosta FA, Nemapate N, Physicochemical and mineralogical characterization of Musina mine copper and New Union gold mine tailings: Implications for fabrication of beneficial geopolymeric construction materials, Journal of African Earth Sciences 137:218-228 (2018). DOI:10.1016/j.jafrearsci.2017.10.016

Gonzalez A, Mamalis P, Research & Innovation Projects relevant to the Circular Economy Strategy CALLS 2016 – 2018: Horizon 2020, European Commission, Research and Innovation (2019)

Grilo J, Faria P, Veiga R, Santos-Silva A, Silva V, Velosa A, New natural hydraulic lime mortars. Physical and microstructural properties in different curing conditions, Construction and Building Materials 54:378-384 (2014). DOI:10.1016/j.conbuildmat.2013.12.078

GTK, Pyhäsalmi Mineral Deposit Report, Geological Survey of Finland (2018)

Hao L, Peixin L, Linlin F, Yan M, Yingli F, Xuesong L, Shaojie L, Feng-qing Z, Preparation of an environment friendly adhesive mortar, Study of Civil Engineering and Architecture (SCEA) 2 (1) (March 2013)

Huang SC, Chang FC, Lo SL, Lee MY, Wang CF, Lin JS, Production of lightweight aggregates from mining residues, heavy metal sludge, and incinerator fly ash, Journal of Hazardous Materials 144(1-2): 52-8 (2007). DOI:10.1016/j.jhazmat.2006.09.094

Heah CY, Kamarudin H, Mustafa Al Bakri AM, Bnhussain M, Luqman M, Khairul Nizar I, Ruzaidi CM, Liew YM, Study on solids-to-liquid and alkaline activator ratios on kaolin-based geopolymers, Construction and Building Materials 35:912–922 (2012). DOI:10.1016/j.conbuildmat.2012.04.102

Hu L, Wu H, Zhang L, Zhang P, Wen Q, Geotechnical properties of mine tailings, Journal of Materials in Civil Engineering 29(2): 04016220 (2017). DOI: 10.1061/(ASCE)MT.1943-5533.0001736

Janković K, Bojović D, Stojanović M, Lončar L, The use of mine tailings as a partial aggregate replacement in SCC concrete, International conference, Contemporary achievements in civil engineering, Serbia (April 2015). DOI:10.14415/konferencijaGFS 2015.007

Jamieson HE, Walker SR, Parsons MB, Mineralogical characterization of mine waste, Applied Geochemistry 57:85-105 (2015). DOI:10.1016/j.apgeochem.2014.12.014

Jemishkumar M, Bharti S, Aruna M, Vardhan H, Utilization of mining wastes in manufacturing of bricks, Conference: National Seminar on Recent Trends in Mechanized Mining, Kothagudem, Telangana, (27-28 December 2014)

Jones H, Boger D, Sustainability and waste management in the resource industries, Industrial and Engineering Chemistry Research 51(30): 10057–10065 (2012). DOI: 10.1021/ie202963z

Jung Ju W, Shin D, Park H, Nam K, Environmental compatibility of lightweight aggregates from mine tailings and industrial byproducts, MDPI-Metals 7:390 (2017). DOI:10.3390/met7100390

Kappel A, Ottosen LM, Kirkelund GM, Colour, compressive strength and workability of mortars with an iron rich sewage sludge ash, Construction and Building Materials 157:1199-1205 (2017). DOI:10.1016/j.conbuildmat.2017.09.157

Kappel, A, Kirkelund, GM, Ottosen, LM, Utilisation of electrodialytic treated sewage sludge ash in cement based materials, 5th International Conference on Sustainable Solid Waste Management, Athens, Greece, 21/06/2017 - 24/06/2017 (2017a)

Kappel A, Pares Viader R, Kowalski KP, Kirkelund GM, Ottosen LM, Utilisation of electrodialytically treated sewage sludge ash in mortar, Waste and Biomass Valorization 9(12):2503–2515 (2018). DOI: 10.1007/s12649-018-0215-z

Kastiukas G, Zhou X, Wan KT, Castro Gomes J, Lightweight alkali-activated material from mining and glass waste by chemical and physical foaming, Journal of Materials in Civil Engineering 31(3): 04018397 (2019). DOI: 10.1061/(ASCE)MT.1943-5533.0002610

Kinnunen PH, Kaksonen AH, Towards circular economy in mining: Opportunities and bottlenecks for tailings valorization. Journal of Cleaner Production 228: 153–160 (2019). DOI:10.1016/j.jclepro.2019.04.171

Kirkelund GM, Jensen PE, Ottosen LM, Pedersen KB, Comparison of two- and three-compartment cells for electrodialytic removal of heavy metals from contaminated material suspensions, Journal of Hazardous Materials 367: 68-76 (2019). DOI: 10.1016/j.jhazmat.2018.12.063

Kiventera J, Golek L, Yliniemi J, Ferreira V, Deja J, Illikainen M, Utilization of sulphidic tailings from gold mine as a raw material in geopolymerization, International Journal of Mineral Processing 149:104-110 (2016) DOI: 10.1016/j.minpro.2016.02.012

Kunt K, Yıldırım M, Dur Fatma, Derun EM, Pişkin S, Utilization of Bergama gold tailings as an additive in the mortar, CBU Journal of Sciences 11(3):365-371 (2015). DOI:10.18466/cbujos.89776

Kuranchie FA, Shukla SK, Habibi D, Mohyeddin A, Utilisation of iron ore tailings as aggregates in concrete, Cogent Engineering 2(1), 1083137 (2015). DOI:10.1080/23311916.2015.1083137

Lin KL, Shiu HS, Shie JL, Cheng TW, Hwang CL, Effect of composition on characteristics of thin film transistor liquid crystal display (TFT–LCD) waste glass-metakaolin-based geopolymers, Construction and Building Materials 36:501–507 (2012). DOI:10.1016/j.conbuildmat.2012.05.018

Longhi A, Rodriguez ED, Bernal SA, Provis JL, Kirchheim AP, Valorisation of a kaolin mining waste for the production of geopolymers Journal of Cleaner Production 115: 265-272 (2016). DOI:10.1016/j.jclepro.2015.12.011

Lottermoser B, Introduction to mine wastes. In: Mine Wastes, Springer Berlin Heidelberg: 1-41 (2010). DOI: 10.1007/978-3-642-12419-8

Magro CC, Guedes PR, Kirkelund GM, Jensen PE, Ottosen LM, Ribeiro AB, Incorporation of different fly ashes from MSWI as substitute for cement in mortar: An overview of the suitability of electrodialytic pre-treatment. In: Ribeiro AB, Mateus EP, Couto N, editors. Electrokinetic Across Disciplines and Continents. New Strategies for Sustainable Development, Springer International Publishing; 2016, p. 225–247. DOI: 10.1007/978-3-319-20179-5_12

Magro C, Paz-Garcia JM, Ottosen LM, Mateus EP, Ribeiro AB, Sustainability of construction materials: electrodialytic technology as a tool for mortars production. Journal of Hazardous Materials 363: 421–427 (2019). DOI: 10.1016/j.jhazmat.2018.10.010

Mapinduzi RP, Bujulu PMS, Mwegoha WJS, Potential for reuse of gold mine tailings as secondary construction materials and phytoremediation, International Journal of Environmental Sciences 7(1): 49-61 (2016). DOI:10.6088/ijes.7005

Melfos V, Voudouris P, Geological, Mineralogical and geochemical aspects for critical and rare metals in Greece, Minerals 2(4):300-317 (2012). DOI:10.3390/min2040300

Müezzinoğlu A (2003) A Review of Environmental Considerations on Gold Mining and Production, Critical Reviews in Environmental Science and Technology 33 (1): 45-71 (2003). DOI: 10.1080/10643380390814451

Mudd G M, Boger DV, The ever growing case for paste and thickened tailings - towards more sustainable mine waste management, AusIMM Bulletin 2: 56-59 (2013).

Muduli SD, Rout PK, Pany S, Mustakim SM, Nayak BD, Mishra BK, Innovative process in manufacturer of cold setting building brick from mining and industrial wastes, The Indian Mining Engineering Journal 49(8):127-130 (2010)

Amrani M, Taha Y, Kchikach A, Benzaazoua M, Hakkou R, Valorization of phosphate mine waste rocks as materials for road construction, Minerals 9:237 (2019). DOI: 10.3390/min9040237

Nadeif A, Taha Y, Bouzahzah H, Hakkou R, Benzaazoua M, Desulfurization of the old tailings at the Au-Ag-Cu Tiouit Mine (anti-atlas Morocco), Minerals 9 (7):401(2019). DOI: 10.3390/min9070401

Newall P, Hill A, Ellis R, King P, Holley S, Richardson S et al., NI 43-101 Technical repot for the Neves-Corvo Mine, Portugal. Wardell Armstrong (2017).

Nilsson L, Nitrogen transformations at the Kiruna mine: The use of stable nitrogen isotopes to trace nitrogen-transforming processes, Department of Earth Sciences, Program for Air, Water and Landscape Sciences. Villav. 16, 752 36 Uppsala (2013)

Oluwasola EA, Hainin MR, Aziz. MMA, Yaacob H, Warid MNM, Potentials of steel slag and copper mine tailings as construction materials, Materials Research Innovations 18:250-254 (2014). DOI:10.1179/1432891714Z.000000000966

Onisei S, Pontikes Y, Van Gerven T, Angelopoulos GN, Velea T, Predica V, Moldovan P, Synthesis of inorganic polymers using fly ash and primary lead slag, Journal of Hazardous Materials 205–206:101–110 (2012). DOI:10.1016/j.jhazmat.2011.12.039

Paiva H, Silva AS, Velosa A, Cachim P, Ferreira VM, Microstructure and hardened state properties on pozzolan-containing concrete, Construction and Building Materials 140:374-384 (2017). DOI:10.1016/j.conbuildmat.2017.02.120

Panias D, Giannopoulou I, Perraki T, Effect of Synthesis Parameters on the Mechanical Properties of Fly Ash-Based Geopolymers. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 301: 246-254 (2007). DOI: 10.1016/j.colsurfa.2006.12.064

Pavez O, González L, Veja H, Rojas E, Copper tailings in stucco mortars, REM- International Engineering Journal 69 (3) (2016). DOI: 10.1590/0370-44672015690148

Peng K, Yang H, Ouyang J, Tungsten tailing powders activated for use as cementitious material, Powder Technology 286: 678-683 (2005). DOI:10.1016/j.powtec.2015.09.012

Peng K, Lv C, Yang H, Novel preparation of glass ceramics from amorphized tungsten tailings, Ceramics International 40: 10291-10296 (2014). DOI:10.1016/j.ceramint.2014.02.121

Peralbo Cano R, Aplicaciones técnico-escultóricas de hormigones y morteros. Caracterización y Normalización (Technical-Sculpture applications of concretes and mortars. Characterization and Standardization), PhD Thesis, Department of Sculpture, University of Granada, Spain (2007)

Pontes J, Santos Silva A, Faria P, Evaluation of pozzolanic reactivity of artificial pozzolans, Materials Science Forum 730-732: 433-438 (2013). DOI:10.4028/www.scientific.net/MSF.730-732.433

Ribeiro AB, Rodriguez-Maroto J, Electroremediation of heavy metal-contaminated soils - Processes and applications. Chap.18. In: Prasad MNV, Sajwan KS, Naidu R, editors. Trace Elements in the Environment: Biogeochemistry, Biotechnology and Bioremediation, Taylor & Francis, Florida, USA: CRC Press, p. 341–368 (2006). DOI: 10.1201/9781420032048

Ribeiro AD, Silva AS, Labrincha JA, Morelli MR, Rheological properties and hydration behavior of portland cement mortars containing calcined red mud, Canadian journal of Civil Engineering 40: 557-566 (2013). DOI: 10.1139/cjce-2012-0230

Romagnoli M, Leonelli C, Kamse E, Gualtieri ML, Rheology of geopolymer by DOE approach, Construction and Building Materials 36:251–258 (2012). DOI:10.1016/j.conbuildmat.2012.04.122

Roy S, Adhikari GR, Gupta RN, Use of gold mill tailings in making bricks: a feasibility study, Waste Management and Research 25(5): 475-482 (2007). DOI: 10.1177/0734242X07076944

Sangiorgi C, Lantieri C, Tataranni P, Castro-Gomes J, Gabriel M, Reuse of mining waste into innovative alkali-activated-based materials for road pavement applications, 4th International Chinese European Workshop (CEW) on functional pavement design, Delft (2016). DOI: 10.1201/9781315643274-191

Sedira N, Magrinho M, Castro-Gomes J, Red clay brick and tungsten mining waste-based alkali-activated binder: Microstructural and mechanical properties, Construction and Building Materials 190: 1034-1048. (2018). DOI: 10.1016/j.conbuildmat.2018.09.153

Shettima AU, Hussin MW, Ahmad Y, Mirza U, Evaluation of iron ore tailings as replacement for fine aggregate in concrete, Construction and Building Materials 120:72-79 (2016). DOI:10.1016/j.conbuildmat.2016.05.095

Sigvardsen NM, Nielsen MR, Potier C, Ottosen LM, Jensen PE, Utilization of mine tailings as partial cement replacement, Modern Environmental Science and Engineering 4(4): 365-374 (2018). DOI:10.15341/mese(2333-2581)/04.04.2018/009

Taha Y, Benzaazoua M, Hakkou R, Mansori M, Coal mine wastes recycling for coal recovery and eco-friendly bricks production, Minerals Engineering 107:123-138 (2016). DOI:10.1016/j.mineng.2016.09.001

Loutou M, Taha Y, Benzaazoua M, Daafi Y, Hakkou, R, Valorization of clay by-product from Moroccan phosphate mines for the production of fired bricks, Journal of Cleaner Production 229:169-179 (2019). DOI:10.1016/j.jclepro.2019.05.003

Pacheco-Torgal F, Desenvolvimento de ligantes obtidos por activação alcalina de lamas residuais das minas da Panasqueira. PhD Thesis, University of Beira Interior, Covilhã, Portugal (2007)

Pacheco-Torgal F, Castro-Gomes JP, Jalali S, Adhesion characterization of tungsten mine waste geopolymeric binder. Influence of OPC concrete substrate surface treatment, Construction and Building Materials 22(3):154–161 (2008). DOI:10.1016/j.conbuildmat.2006.10.005

Pacheco-Torgal FP, Shasavandi A, Jalali S, Using metakaolin to improve the sustainability of fly ash based concrete, INVACO2: International Seminar, Innovation and Valorization in Civil Engineering and Construction Materials, N 1P-251, Rabat, Morocco (November 2011)

Sameer S, Bringezu S, Life cycle input indicators of material resource use for enhancing sustainability assessment schemes of buildings, Journal of Building Engineering 21:230-242 (2019). DOI: 10.1016/j.jobe.2018.10.010

Sandanayake M, Zhang G, Setunge S, Estimation of environmental emissions and impacts of building construction – A decision making tool for contractors, Journal of Building Engineering 21:173-185 (2019). DOI:10.1016/j.jobe.2018.10.023

Taha Y, Benarchid Y, Benzaazoua M, Environmental behavior of waste rocks based concrete: Leaching performance assessment, Resources Policy (2019). DOI: 10.1016/j.resourpol.2019.101419

Ullas SN, Reddy V, Rao KSN, Characteristics of masonry units from iron ore tailings, International conference on Sustainable Built Environment (ICSBE), Kandy, 108-114 (2010)

UN- United Nations, Department of Economic and Social Affairs, Population Division (2018). The 2018 Revision of World Urbanization Prospects.

US EPA, Environmental Protection Agency, Report to Congress on Wastes from the Extraction and Beneficiation of Metallic Ores, Phosphate Rock, Asbestos, Overburden from Uranium Mining, and Oil Shale, Report No. EPA/530-SW-85-033, Washington, DC (December 1985)

Yang KH, Cho AR, Song JK, Effect of water–binder ratio on the mechanical properties of calcium hydroxide-based alkali-activated slag concrete, Construction and Building Materials 29:504–511 (2012). DOI:10.1016/j.conbuildmat.2011.10.062

Yongliang C, Yamin Z, Tiejun C, Yunliang Z, Senxu B, Preparation of eco-friendly construction bricks from hematite tailings, Construction and Building Materials 25:2107-2111 (2011). DOI:10.1016/j.conbuildmat.2010.11.025

Załoziński R, KGHM: Importance of silver in portfolio of fully integrated mining company, The LBMA/LPPM Precious Metals Conference, Rome (October 2013)

Zhang H, Wang H, He X, Guo S, Xia Y, Zhou Y, Liu K, Yang S, Research progress, problems and prospects of mine water treatment technology and resource utilization in China, Critical Reviews in Environmental Science and Technology (2019). DOI: 10.1080/10643389.2019.1629798

Zhao Y, Zhang Y, Chen T, Chen Y, Bao S, Preparation of high strength autoclaved bricks from hematite tailings, Construction and Building Materials 28(5): 450-455 (2012) DOI: 10.1016/j.conbuildmat.2011.08.078