Each year, nearly 40 billion tonnes of raw materials extracted from the Earth’s crust feed into the construction industry. The associated material flows dramatically contribute to anthropogenic CO₂ emissions. Therefore, more sustainable supply chains must be envisaged based on the use of locally available resources and the principles of circular economy. Drawing inspiration from vernacular architecture, innovative solutions for green construction based on sustainable exploitation of local resources can be posited. This strategy has also inspired the proposed practice of in situ resource utilization on planetary bodies such as the Moon and Mars.

**Keywords:** circular economy; supply chains; earthen construction; in situ resource utilization (ISRU)

**INTRODUCTION**

Reconciling the need of meeting the demand for reliable, durable, and cost-effective building materials, while minimizing the impact on the environment, poses a societal conundrum and an extraordinary technological challenge. To help provide a picture of the environmental burden associated with construction materials, it is useful to report some figures from the Circularity Gap Report (Circle Economy 2020). The report’s authors estimate that the global annual resource footprint for all forms of consumption is about 100 billion tonnes of material, comprising minerals (in the broadest sense), fossil fuels, and biomass. More than 90% of this stock is extracted as virgin materials, with the weight of recycled resources being less than nine billion tonnes. About one third of the overall resource (virgin + recycled) stream is collected as waste, the majority of which is unrecoverable after dispersion in the environment by landfelling, incineration, or other practices. More than 40% of the total resource (virgin + recycled) stream feeds into the construction sector, which is also responsible for 13.5 billion tonnes of greenhouse gas emissions (Circle Economy 2020) and about 30% of the total energy consumption (International Energy Agency 2020). These figures demonstrate an urgent need to drive the construction industry toward sustainable practices by deploying innovative solutions capable of mitigating (a) negative impacts on landscapes by large-scale quarrying and mining operations; (b) overall volumes of virgin raw materials and unrecovereable waste; and (c) CO₂ emissions associated with extraction and processing of raw materials. Apart from the intrinsic impact on the environment, the progressive depletion of raw materials related to construction may also trigger societal issues. An example is sand, gravel, and crushed rocks that are used as inert aggregates in concrete and constitute the most extracted category of material, amounting to nearly 30 billion tonnes in 2017, with annual demand projected to double by 2060 (Organisation for Economic Co-operation and Development 2019). The huge demand has triggered illegal extraction activities, particularly in developing countries, controlled by criminal groups (“sand mafias”) that sell on the black market. The rise of illegal sand mining also exposes local communities to environmental hazards where extractive industries adversely affect coastline morphodynamics and accelerate coastal erosion (Fig. 1).

The case study illustrated in Figure 1 exemplifies the need for coping with landform modifications set off by quarrying and mining activities.

The progressive increase of environmental impacts induced by human activities has led a group of geologists and other scientists to propose the introduction of a new unit within the geological time scale, named the Anthropocene. According to the proposers, the beginning of this new epoch should correspond to the mid-20th century, when a sharp rise in population growth (the Great Acceleration) induced a tremendous increase in the alteration of ecosystems as a result of intensive farming and industrial activity (Zalasiewicz et al. 2019). Strictly related to the Anthropocene is the concept of the “technosphere” (or “anthrophosphere”), which comprises all humans and their artifacts, including buildings, infrastructure, and associated waste. The mass of the technosphere has been estimated to be 30 trillion tonnes, 10% of which consists of the total mass of concrete produced throughout the history of mankind (Waters et al. 2016).

**SUSTAINABLE RAW MATERIAL SOURCING AND SUPPLY CHAINS**

As stated in the introduction, the construction and building industry consumes a significant share of the resources extracted globally, in addition to contributing to a fair amount of the overall CO₂ emissions and energy consumption. Current strategies for mitigating the cumulative environmental footprint associated with cement and concrete production include (a) partial replacement of Portland cement cinder with blends containing variable
amounts of supplementary cementing materials (SCM), such as natural pozzolans (including calcined clays), carbonaceous fillers, and Si-rich biomasses consisting of agricultural waste and Si-Al-Ca-rich industrial waste or byproducts (Scrivener and Snellings 2022 this issue); (b) production of non-Portland binders based on the reaction of the above SCM in alkaline solutions or on the processing of raw materials other than limestone (Hanein et al. 2022 this issue); and (c) use of recycled aggregates in place of primary sand and gravel. These may be obtained, for example, by processing and sorting construction and demolition waste, which is estimated to be generated at a rate of over three billion tonnes per year globally (Akhtar and Sarmah 2018). Returned concrete represents another possible source of recycled aggregates. It is estimated that, annually, over 125 million tonnes of unused concrete are returned from construction sites to production plants. Aggregates with properties comparable to natural aggregates can be obtained by processing returned concrete (Ferrari et al. 2014).

The use of waste and by-products in cement and concrete has the double advantage of both mitigating the CO₂ footprint embodied in these commodities and recovering materials at the end of their life cycle. This, in turn, can relieve the pressure exerted on primary deposits of raw materials and disposal facilities such as landfills and incinerators. Although the available volumes of such waste materials will not be able to meet the entire demand for building materials everywhere, a virtuous approach could be envisaged by which tailor-made recipes for cement and concrete are conceived based on the local availability of recycled resources and specific needs in terms of engineering properties and architectural style. This requires a paradigm shift from the current one-size-fits-all approach based on the adaptation of a universal material, such as Portland cement, to different geographical, climatic, and cultural contexts.

As an example of how waste materials can be recycled into construction products, metallurgical slags from the steel industry have perhaps been the most studied and implemented secondary raw material in cement. The slag obtained in the smelting of ore to pig iron has a chemical composition similar to that of Portland cement. Quenching, granulation, and subsequent grinding of this slag results in a powder (ground-granulated blast-furnace slag, GGBFS) mostly composed of alumino-silicate glass, with minor amounts of crystalline phases such as merwinite (Ca₂MgSi₂O₇) and phases within the åkermanite–gehlenite (Ca₂MgSi₂O₇–Ca₂Al₂SiO₇) solid solution. Ground-granulated blast-furnace slags can be used in blended or alkali-activated, low-carbon cements (Hanein et al. 2022 this issue; Scrivener and Snellings 2022 this issue). The global availability of GGBFS, as estimated by the U.S. Geological Survey, is 300–360 million tonnes. This can vary widely in different geographical locations. For example, the extent of the steel industry in all African countries except South Africa is very limited (the World Bank estimated 300 thousand tonnes of slag exported from South Africa in 2019, whereas the amount exported from all other African countries was 500 tonnes; data retrieved from wits.worldbank.org on 30 September 2021). Slags other than GGBFS generated in the conversion of pig iron to steel and those obtained by processing non-ferrous metal ores, such as in the production of copper, can potentially be used, especially in the absence of locally available GGBFS (Gabasiane et al. 2021). However, their application potential is much lower than that of GGBFS, mostly because of their highly variable chemical compositions (including heavy metals), high crystallinity, and poor reactivity in aqueous media. These metallurgical slags can also replace primary fine and coarse aggregates in concrete, although they may be prone to volume expansion, leading to undesired effects.

Fly ashes produced during coal combustion have also received much attention as secondary raw materials for the cement industry because pledges to phase out coal in favor of less impacting fuels have not yet translated into actions that drastically reduce global coal consumption. Coal combustion fly ashes have variable compositions, with contents of SiO₂ and Al₂O₃ that may vary in the ranges of 35%–70% and 15%–35%, respectively. These ashes mostly consist of amorphous spherical, sometimes hollow, particles (cenospheres) of micrometer size, with minor crystalline phases such as mullite and magnetite. In the short term, coal fly ashes may represent a valuable waste material to be used in the production of alternative cements. However, coal fly ash cannot be deemed a suitable resource over the long term because the above-mentioned phasing out of coal as a source of energy is accompanied by an increase in the share of alternative fuels for coal combustion, which results in ashes that are less suitable for use in cements (Millward-Hopkins et al. 2018).

The dimension stone industry also produces large amounts of waste that can be incorporated into cementitious binders. The gross dimension stone production has doubled in the last two decades, reaching a value of over 300 million tonnes in 2019. The amount of waste derived from quarrying and processing has remained stable over this period, constituting up to 70% of the gross production (Fig. 2). The >200 million tonnes produced in 2019 represent a tremendous amount of waste, which simultaneously poses serious issues and challenges in terms of disposal, but also an opportunity in terms of waste recovery and reuse. A portion of this waste can be used as coarse and fine aggregates in concrete or as filler in cement. More than 50% of global stone production is represented by calcareous stones such as limestone and marble. Waste, in the form of slurry, is produced during quarrying, cutting, and
polishing of such calcium carbonate rocks. The disposal of this slurry constitutes a severe environmental issue because it can contaminate water (leading to variations in pH and turbidity) and affect the properties of riverbeds and soils (the physical action of the slurry can consolidate and induce impermeabilization). By drying marble slurries, a powder consisting of variable amounts of calcite (depending on the purity of the source deposit) can be obtained and used in significant amounts in various types of alternative cements.

In general, industrial residues may contain variable amounts of potentially hazardous substances, such as heavy metals, radioactive elements, respirable crystalline silica, or harmful organic compounds. Limit values are usually set by local legislation on either the total content or emissions to the air, groundwater, etc. The ability of cement and concrete to immobilize hazardous substances must therefore be demonstrated, e.g., through standardized leaching tests.

**PRODUCTION SCENARIOS FOR SUSTAINABLE CONSTRUCTION MATERIALS**

The primary and recycled raw materials for construction are processed and transported in bulk using economies of scale, which has known environmental impacts. The one-size-fits-all approach has lower legal and financial risk relative to solutions using locally available recycled resources. Tailor-made solutions do not always have proven long-term feasibility or documented environmental consequences for particular applications. The potential for unintended environmental impacts, issues with the scale-up of operations, and whether a given alternative solution will match local demand for bulk materials, all constitute risks. The ultimate issue for the adoption of innovative construction materials is the risk to business sustainability, particularly in a market of open competition where the price of raw materials relates to a large proportion of the overall micro-economic model. This is a similar issue for raw material producers operating at all scales and in all commodities, where high efficiency is a mechanism to keep unit costs and, thereby, material costs low for the rest of the supply chain (Moore et al. 2020). The reasons why virgin materials are more attractive propositions than recycled materials for construction are therefore dominantly economic, and they connect raw material producers and raw material users.

The UK National Engineering Policy Centre (National Engineering Policy Centre 2021) tied the embodied and operational carbon performances of the built environment to the use of raw materials via procurement practices, but stated that, “Current profit margins in the construction sector are not suitable for achieving the net zero transformation, failing to encourage both innovation and decarbonization. Future business models need to take a different approach to productivity performance and risk to stimulate greater innovation in the sector which can in turn stimulate decarbonization.” The authors recommend a change in the behavior of the construction industry, emphasizing reuse over recycling of construction materials, which maintains the quality of materials as well as reducing the carbon footprint, and the use of low-carbon design using low-carbon and nature-based materials. Where recycled and alternative resources are locally sourced, they may be present in far smaller volumes than traditional near-surface reservoirs of construction materials. A reduction in the efficiencies of scale for bulk construction materials challenges the financial viability of tailor-made solutions for environmentally sustainable construction. The reality is that a sustainable resource is usually a more costly resource, relative to conventional construction materials. Solutions proposed to address the issues of scale in the mining sector include low capital expenditure, low carbon, and low impact platform technologies to try to reduce competitive disadvantages (Moore et al. 2021).

The proof of viability for different types of raw materials, and therefore business risk, lies with the platform developer, who needs to be able to respond to user demands. Recent trends in materials research and small-scale processing solutions support small and medium enterprises that take the risks associated with development. Market entry and expansion depend upon a culture of adoption of new materials at a potentially higher cost, but the cost is not simply a function of commodity price. If waste also has a high cost, then a movement from a linear take-make-waste supply chain to a circular economy may serve to reduce the waste and carbon footprint. In 2012, the landfill tax in the UK increased from £2.50 per tonne of inert material that did not count toward the EU biodegradable landfill targets to the same full rate of £64 per tonne that applied to active wastes. As well as incentivizing material reuse and recycling, the change led to fears about the sustainability of the construction sector and illegal tipping. Governments incentivize construction companies to engage in responsible practices via interventions such as compensation at a higher rate than the cost of disposal (Chinese government intervention; Liu et al. 2019). This approach effectively removes waste disposal costs from construction material providers and companies that are considering the financial viability of alternative construction materials produced by relatively small-scale bespoke solutions.

Market entry is challenging where the production cost for alternative construction materials is greater than that for conventional construction materials. In a circular economy where wastes are converted into alternative construction materials, the higher cost of bespoke solutions can be lower than the total cost of conventional raw materials plus waste disposal charges. Market entry is also challenging in scenarios where (a) different stakeholders bear the costs of construction materials and waste
disposal so that conventional materials remain very low cost to the construction sector; (b) the reduction of waste volume is inadequate to offset higher material costs; and (c) no culture exists for the adoption of environmentally beneficial practices that reduce profit margins. However, the increasing demands of society to adopt more sustainable practices drive whole-system approaches toward stakeholder connectivity in circular economy models. Critical analysis of vertical integration in the supply chain shows that advantages related to quality standards, credibility for new products, supply assurance, and market power tend to outweigh higher production costs and risks of concentrating on non-core operations (Kaiser and Obermaier 2020). Research into the circular economy creates an understanding of where policy interventions may best be placed to change the nature of incentives toward new models of best practices and new behaviors in raw material production.

CASE STUDIES FROM EMERGING ECONOMIES: THE AFRICAN SCENARIO

The African continent represents an exemplary scenario because Africa has the largest urbanization rate in the world and, currently, is a net importer of cement. Alternative approaches to local raw material sourcing and cement production will generate a massive impact on this continent, likely inspiring the rest of the world. Schmidt et al. (2020) posited that future African urban concrete demand will significantly increase the already-high climate impact. To limit carbon emissions from the consumption of concrete, researchers and engineers on the African continent have been encouraged to place much attention on alternative materials. Marginalized resources that have the potential to provide sustainable remedies include agro-based waste, locally available mining waste, and other secondary raw materials, as well as natural pozzolans and clay soils that could be used for earthen construction (the practice of construction using unfired, untreated, raw earth). In general, the implementation of tailor-made solutions in specific geographical contexts, such as the African continent, may impact the environment less negatively than the adoption of standards and solutions conceived for one-size-fits-all scenarios from the Global North.

Use of Alternative Raw Materials

Agro-based waste can be used to deploy bespoke solutions in construction in different ways. In concrete, agro-based waste could be used as coarse aggregates or fibers to reduce the weight and cost of concrete with a significant enhancement in mechanical properties (Savastano et al. 2000). In binders, some ashes of agro-based waste materials could be used as a partial replacement for Portland cement without compromising the overall performance. Examples of ashes successfully used as SCM (Charitha et al. 2021) are those obtained by burning sugarcane bagasse, rice husks, cassava peels, palm kernels, coconut shells, wheat straw, corn cobs, groundnut husks, bamboo leaves, and others. In particular, rice husk ash (Fig. 3) has been demonstrated to represent a valuable waste material with excellent binding potential, both in blends with Portland cement and when activated by alkaline solutions (Thomas 2018). It is estimated that 20% of the overall rice production is represented by husks, 20% of which consists of an inorganic residue of soluble silicate glass (Battegazzore et al. 2014) formed upon husk incineration and by minor amounts of cristobalite (mostly cristobalite). Moreover, extracts from plants are used as novel and cost-effective water-reducing bio-admixtures to enhance the fresh properties of concrete and mortar. Examples of bio-admixtures include starch from potatoes and cassava, a water extract from cactus, palm liquor from palm trees, and aqueous extract from okra (Hazarika et al. 2018). Although such agro-based secondary resources have been shown to be an efficient replacement for other primary resources, there may be concerns about the viability of large-scale production and competition with other productive sectors (e.g., the fertilizer industry).

Clam shells represent another example of local materials that can be sourced in substitution of calcium carbonate quarried from limestone deposits. They are classified as industrial mineral resources by some local mining and mineral authorities (Afeku and Asamoah Debrah 2020) and, considering the scarcity of high-purity limestone deposits in many Sub-Saharan countries, can potentially be used in blended cements that incorporate ground calcium carbonate (Screivener and Snellings 2022 this issue).

Earthen Constructions

Earthen construction materials have a long history of use in Africa. Many buildings in rural parts of Sub-Saharan African countries are made from earth materials, with relatively good durability and few indications of deterioration. Earthen materials are arguably one of the most eco-friendly and cheap raw materials for low-rise housing and represent a viable option to tackle the housing demand in many African countries where the higher costs for conventional construction materials based on Portland cement pose problems. In addition to low costs and environmental benefits, earthen constructions are characterized by excellent thermal comfort, thus representing a suitable option in hot climates.
Typical earthen materials for construction (Fig. 4) include adobe (building material made from earth and organic materials), rammed earth (a technique using compacted natural raw materials such as earth, chalk, lime, or gravel), and compressed earth blocks, which can also be stabilized by the addition of relatively small amounts of cement binders (commonly 5%–8%). The stabilization of earthen materials with cement binders enhances their mechanical properties and durability, especially when the surfaces of earthen constructions are exposed to moisture or rain. However, the increased environmental impact associated with the addition of Portland cement is comparatively higher than the gain in strength, hence the need for adopting more sustainable solutions to the stabilization of these materials. While earthen construction materials provide economic and environmental sustainability in comparison with cement-based construction materials, there is still a limited scope for earthen materials in buildings owing to limitations that include (a) the absence of national standards for earthen construction; (b) negative perceptions and an association with poverty, with subsequent poor societal acceptance; and (c) low levels of awareness of the properties and performances of such materials. To change the perception and attitude toward earthen materials, research efforts should be directed toward technological solutions aimed at improving their strength and workability, without compromising the environmental performance and compatibility with specific cultural and geographical contexts. The use of alternative stabilizers with a reduced ecological footprint, which could be based on alkali-activated clays (Marsh et al. 2019) and rice husk ash, might pave the way toward a new generation of earthen constructions.

IN SITU RESOURCE UTILIZATION ON THE MOON AND EXTERNAL PLANETS

Sourcing of raw materials for construction based on sustainable supply chains and a circular economy are also relevant for extraterrestrial construction, given the renewed interest in planetary and space exploration. Transportation of construction materials from the Earth to the Moon to build habitable lunar bases would require an enormous investment. Therefore, it is mandatory to examine opportunities for the implementation of manufacturing approaches based on in situ resource utilization (ISRU). From this perspective, one possible solution to satisfy the need for building materials on the Moon is using lunar regolith to produce cement and concrete in situ. The average bulk chemical composition of lunar regolith is similar to that of coal combustion fly ash, which is commonly used in blended and alkali-activated cement (Pilehvar et al. 2020). Its mineralogical composition consists of plagioclase and pyroxene as major crystalline phases, olivine, and up to 40% aluminosilicate glass (Papike et al. 1982). The crystalline fraction is larger than that of common SCM, such as fly ash, used in blended and alkali-activated cement, implying a reduced intrinsic reactivity in aqueous solution. Nonetheless, it has been observed that alkaline activation can be effective in triggering the development of appropriate engineering properties, including in starting materials containing less than 50% reactive amorphous fraction (Mascarin et al. 2022).

As proof of concept, dedicated studies have been carried out to assess the feasibility of 3D printing using binders produced by alkali activation of regolith simulants (Pilehvar et al. 2020). Such “lunar cement” displayed promising mechanical properties, as well as good extrudability, especially when combined with small quantities of urea (Fig. 5), an ingredient that could also be obtained in situ. Although ISRU of lunar regolith has the potential to drastically reduce the volume of materials transported from the Earth, high additional costs (e.g., for facilities needed to source water and alkali from lunar soil via microwaves and electrolysis) should be accounted for. Moreover, criticalities and possible disruptions of supply chains may occur despite the extensive availability of regolith on the Moon, because the robust maintenance of technological equipment is problematic in remote and inhospitable locations. In situ resource utilization approaches for infrastructure construction on Mars likewise have been posited. Such a prospective implementation is based on the possible use of Martian soil and local volcanic ashes for the production of cement binders, whereas crushed basalt could be used to produce aggregates for concrete. The use of sulfur, extracted from sulfides and sulfates present at the Martian surface (King and McLennan 2010), as a binding agent to produce concrete has also been investigated. Concrete was obtained by mixing sulfur heated at 120 °C with a Martian soil simulant in proportions of approximately 1:1. After cooling, a hardened material with a compressive strength larger than 50 MPa was obtained (Wan et al. 2016).

Studies on construction materials for ISRU are more than intriguing scientific curiosity about the future of mankind, because they may inspire novel construction technologies back on planet Earth and potentially pave the way to a more sustainable management of raw materials. Such virtuous approaches should be aimed at maximizing the use of
locally available primary and secondary resources and
minimizing transport and its associated environmental
footprint, as well as the environmental impact associated
with large-scale quarrying.

CONCLUDING REMARKS
Building materials have played a fundamental role in
society throughout the history of mankind. Cement
and concrete, in particular, will continue to be key commodities
that sustain demographic, urban, and economic growth.
The ongoing discussion on cement and concrete sustain-
ability is heavily focused on CO2 emissions. However, as
argued in this contribution, there is also a strong need
to mitigate the consumption of primary raw materials.
Estimations based on the current rates of raw material
sourcing predict that, by 2050, the consumption of raw
materials will double from the current 90 billion tonnes
per year (Circle Economy 2020). Therefore, it is crucial
to deploy strategies aimed at enhancing the circularity of
the construction industry, and possibly maximizing the use of
locally available resources. One key action will be the
revision and adaptation of existing standards to include
secondary resources that prove adequate for the formula-
tion of alternative cements. This will require joint effort
and coordination between fundamental and applied
research on one side, and standard authorities on the other.
From a more general point of view, the transition toward
sustainability in the construction sector will require a
multidisciplinary approach and collaboration of academic
research with all involved stakeholders, including industry,
policy makers, and local communities. This partnership
should foster a paradigm change, from a one-size-fits-all
approach to a strategy driven by local availability of resources that
account for the local social and cultural contexts.

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